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Acoustic Monitoring of Threatened and Endangered Species in Inaccessible Areas

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14. ABSTRACT
This project developed acoustical systems for monitoring of wildlife sounds over large areas where access is limited. These systems were tested at Fort Hood, Texas, where Golden-cheeked Warblers and Black-capped Vireos are managed intensively. A balloon system was designed to carry digital audio recorders across inaccessible areas. Horn-loaded microphones were developed to provide lightweight acoustical sensors that were highly sensitive to bird songs and deemphasized low-frequency noise from military training activity. The balloon control system included GPS track logging, altitude control, and bidirectional wireless communications.

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Acronyms and Abbreviations

ARU	Autonomous recording unit
BCVI	Black capped vireos
BCS	Bird conservation score
BEVI	Bell’s vireo
BRP	Bioacoustics research program
CFR	Code of Federal Regulations
COTS	Commercial, off-the-shelf
DICK	Dickcissel (or Dicksissel)
FAA	Federal Aviation Administration
FISP	Field sparrow
GCWA	Golden cheek warblers
GPS	Ground positioning system
GRSP	Grasshopper sparrow
LASP	Lark sparrow
OEM	Original equipment manufacturer
PABU	Painted bunting
PIF	Partners in Flight
RCSP	Rufous-crowned sparrow
SERDP	Strategic Environmental Research and Development Program
STFL	Scissor-tailed flycatcher
TES	Threaten and endangered species
UNKN	Unknown
YBCU	Yellow-billed cuckoo

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The project has utilized the following Bioacoustics Research Program staff: Electrical engineering: Tom Calupca (autonomous recording system) and Robert MacCurdy (microphones and signal conditioning), Alejandro Purgue (automatic sound generator, flight control software, and field support); Mechanical engineering: Tom Fowler (aerial platform development); Software engineering: Kathy Dunsmore (acoustic localization), John Burt (multichannel data acquisition software), Jason Adaska (signal recognition), Christina Ahrens (multi-channel signal display), Harold Figueroa (XBAT development); Field recording and expert bird identifications: Chris Tessaglia-Hymes; Data archiving and management: Melissa Fowler. Ann Warde merits special mention for managing and processing enormous BCVI data sets and working efficiently with Fristrup from afar. Russ Charif participated in many phases of the work, including managing field teams and the principal investigators.

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Executive Summary

This project developed acoustical systems for monitoring of wildlife sounds over large areas where access is limited. These systems were tested at Fort Hood, Texas, where Golden-cheeked Warblers (GCWA) and Black-capped Vireos (BCVI) are managed intensively. A balloon system was designed to carry digital audio recorders across inaccessible areas. Horn-loaded microphones were developed to provide lightweight acoustical sensors that were highly sensitive to bird songs and deemphasized low-frequency noise from military training activity. The balloon control system included GPS track logging, altitude control, and bidirectional wireless communications. Balloons could be programmed to automatically land after transiting a designated flight zone.

A total of 33 flights were conducted during spring and summer field seasons in 2002 – 2004. Collectively, these flights drifted 422 km during 856 minutes. Between field seasons, refinements were made in balloon and payload designs that resulted in lower system weight, greater reliability, and improved ease of recovery. Balloon systems using the latest design were flown 14 times in May of 2004, detecting 48 species of birds during 558 minutes of flight spanning 243 kilometers. Data for 11 species were analyzed to estimate song intervals, average range of detection, and numbers of birds detected.

Extensive ground recordings of BCVI songs were obtained to develop and test automatic detection and classification software. Nearly three-quarters of a million BCVI songs were identified from a sample of nearly five million candidate sounds detected in more than 22,000 hours of recordings.

Small, drifting balloons provide an outstanding platform for detecting bird songs, and it is feasible to launch multiple systems per morning. To realize more reliable flight performance, additional design effort should focus on terrain following (disabling altitude control when being advected) and more rapid descent (larger helium valve aperture). Balloons have long been a valuable method for collecting meteorological data, and this project demonstrates their value for wildlife monitoring.

Objective

This project was developed in response to SERDP Statement of Need CSSON-01-01: “Advanced Techniques to Inventory and Monitor Threatened and Endangered Species in Inaccessible Areas.” The immediate goal of the advanced techniques was to extend inventories into areas of military installations that are inaccessible for biological survey personnel. Additional features of the advanced techniques could be elimination of the potentially biasing effect of human observers (wildlife responses to observers, eccentricities in observer perceptual capabilities) and the capacity to more rapidly inventory large areas.

This project developed an aerial acoustical survey system. This system integrated the capacity to detect and identify animal vocalizations at ranges of several hundred meters with a balloon system that drifted with the wind at a controlled altitude. Fort Hood was chosen as the location to test the aerial acoustical survey system. Fort Hood contains the largest populations of the endangered Golden-cheeked Warbler (GCWA) and Black-capped Vireo (BCVI) under a single management authority. The size of the limited access area at Fort Hood (29,000 ha) and the limited ranges of detection for GCWA and BCVI presented substantial challenges for the proposed system.

This project pursued two hardware systems and a suite of processing software to realize objectives of the Statement of Need:

- Lightweight, low-power autonomous recording units that monitor wildlife acoustic activity for many weeks without operator attention.
- A balloon system to carry acoustical instruments at a controlled altitude, and that is easily launched, tracked, and recovered.
- Software tools to rapidly process acoustic data recorded by the digital recording systems to yield logs of calling events, measurements that characterize the structure of each sound, and the capacity to measure the direction of arrival or location of each sound recorded by an array of sensors. The logs produced by this software were designed to be readily imported into statistical processing packages to develop algorithms for species identification and the capacity to automatically produce maps and other graphical summaries of the data.

Background

Many military installations manage species listed as threatened or endangered (TES) in accordance with the Endangered Species Act. Integrating endangered species management with the primary mission of military readiness presents challenges. In particular, population censuses are traditionally performed by biological observers that intensively sample the study area. This is incompatible with live fire training activity, and inconvenient for many other training areas. In response to CSSN-01-01, the Bioacoustics Research Program (BRP) at Cornell University’s

Laboratory of Ornithology proposed to develop an aerial acoustical monitoring system. In January 2001, a three-year contract (SI-1185) was awarded by SERDP.

Animal sounds offer several advantages for autonomous censuses. An inexpensive microphone can be devised that detects sounds from songbirds, insects, and frogs at ranges of several hundred meters. The panoramic survey capability of this sensor stands in dramatic contrast to imaging systems, which usually monitor a very limited solid angle, and must devote tens or hundreds of pixels per target for identification. Acoustical recorders are less expensive, more compact, lighter in weight, and consume much lower power than digital camera or video recording systems. Acoustical data can be recorded much more compactly and are much easier to process automatically than image data.

In order to conduct an acoustical census of inaccessible areas at many military bases, an aerial platform to carry the digital recorders is essential. Even with extraordinary engineering effort (arrays of specialized microphones and associated beamforming detection software), it would be impossible to detect most songbird sounds beyond 1 km. Geometrical spreading losses at 1000 meters are 60 dB, and atmospheric absorption causes an additional loss of 30-100 dB. These formidable figures are actually optimistic, because daytime vertical temperature profiles typically create refractive regimes that impose more severe limits on maximum range of detection.

The acoustical survey system has to be mobile, and there are several acoustical advantages to an aerial platform. Once aloft, the range of detection is largely free from constraints imposed by refraction, the background noise level at the sensor is substantially reduced, and loud songs from nearby birds are no longer present to mask the songs of more distant birds.

Although a powered aerial system offers substantial advantages for navigational control, the project focused on a drifting balloon system. The balloon system is simpler and less expensive to build, lighter in weight, easier to operate, and it poses negligible hazards to other aircraft. A drifting balloon is an ideal listening platform: it can be intrinsically silent and there is no noise from air flowing past the sensor, regardless of wind speed. Lastly, a powered aircraft is more likely to disturb wildlife. A small plane would resemble an aerial predator in profile and movement patterns, and aircraft noise would alert animals to its presence.

The primary design objectives for the balloon system were to minimize its weight (and therefore its size), to provide simple systems to control altitude and log the flight path, and to simplify recovery of the system. Minimal system weight is dictated by several considerations. First, the FAA imposes mandatory flight safety regulations on balloons above a specified size and weight (CFR 101.1). The Cornell system aimed to be substantially smaller than these regulatory limits to eliminate any chance of creating a hazard for other aircraft in the Fort Hood airspace, or any hazards while landing. Smaller balloons require less helium, so they can be launched more rapidly and each launch is less costly. System recovery was simplified by programming each balloon to descend automatically after completing the desired drift, by transmitting balloon location while in flight, and by activating a radio recovery beacon upon descent. In principle, one person could launch and recover several small balloons in a morning.

Compact digital audio recorders played two roles in this project. The aerial platform required one to collect the survey data from each flight. Data from each flight can be used to identify each

song to species, to estimate the typical song intervals for the species detected, and to estimate the range of detection for each species. Typical song intervals must be estimated to identify how many individuals are responsible for the sounds of a chorus, and the range of detection is needed to estimate the area surveyed (which may be different for each species). Thus, the balloon system can estimate how many birds of each species were detected and the area surveyed without any supplementary data. To produce a population estimate, supplementary data are required to ascertain the probability that a bird would not sing while the balloon system was in range. In line transect survey theory (Buckland et al), this factor is termed *g(0)*, or the probability that an animal on the survey track is detected. At Fort Hood, autonomous recording units (ARUs) and microphone array systems were used to capture patterns of singing activity.

Software tools that could support automated detection and identification of millions of songs was developed. These tools were not essential to analyze the balloon flight data, as each flight generated less than one hour of data. However, the ARU data was much more voluminous, so it was impractical to have expert listeners review all of these recordings. A principal design goal for the software systems was an intuitive, graphical user interface that encouraged naïve users to explore their data. Detectors should be easy to configure and test, detection results should be displayed graphically to foster intuitive understanding of performance, signal measurements should be readily displayed graphically or in tabular form, and it should be easy to export measurements to other software packages for statistical analysis and graphical presentation. Thanks to synergistic interactions with other research projects in the Bioacoustics Research Program, two platforms for signal analysis were developed. One is a standalone program of moderate complexity; the other is a Matlab library that offers a much richer spectrum of features and extensibility.

Fort Hood, in central Texas, was chosen as the field site for development and testing. Field effort focused on two endangered songbirds: the black-capped vireo (*Vireo atricapillus*, BCVI) and the golden-cheeked warbler (*Dendroica chrysoparia*, GCWA). Fort Hood supports the largest remaining populations of these two birds under a single management authority (The Nature Conservancy, 2000). The U.S. Fish and Wildlife Service issued a Biological Opinion requiring Fort Hood to collect survey data on endangered species on all areas of the installation, including the 25,000 ha Live-Fire Area, and the 4,000 ha Dudded Impact Area.

Materials and Methods

The central component of this project is an autonomous recording unit (ARU), which can be deployed either on the ground or floated above the ground using a helium balloon system. Flash RAM or miniature hard disks are used to store the data, with the latter providing several weeks of recording capacity. The size, weight, and power consumption of these components were minimized to facilitate rapid deployment and render the instruments inconspicuous. Custom electronic systems were developed to provide scheduled recording capability and up to 8 channels of recording capacity. ARU systems record data that are subsequently processed to detect, identify, and optionally locate each sound. Recordings were obtained using ARUs at fixed locations on the ground, in order to obtain long-term data regarding singing behavior that could be used to develop automatic detection and classification algorithms.

A helium balloon system was developed to float acoustic monitoring systems. A drifting balloon was chosen because it provides a relatively simple, economical, and easily deployed platform. A drifting balloon provides an ideal platform for audio recording, because turbulence and self-noise are negligible. Professional weather balloons were used for this project (Edmund Scientific #3060568, #3072151). The reinforced necks of these balloons provided a secure connection to the payload, which was suspended beneath the balloon.

The balloon sensed altitude and vented helium or water using custom valve systems to maintain a desired flight profile. The balloon also monitored GPS position using a Trimble Lassen LP OEM module. Custom microcontroller systems were used to maintain balloon buoyancy, log navigation data, manage wireless communications, initiate descent, and activate recovery aids. The initial prototypes utilized three PicStick microcontrollers from Micromint, Inc. The 2003 and 2004 systems utilized a custom system using twin MSP430 microcontrollers from Texas Instruments. The navigation and control computer maintained an archival navigation and equipment status log.

Bidirectional wireless communications were implemented in 2004 using the Xstream OEM RF module from MaxStream, Inc. These modules utilized a frequency-hopping, spread spectrum protocol in the 900 MHz ISM band, and offer 19200 bps communications through an RS232 interface. The modules weighed 24 grams. Maximum communication ranges of up to ten miles were realized in the field, and these systems were capable of implementing a peer-to-peer network to link up a series of balloons with personnel in a recovery vehicle. Flight control systems could be fully reprogrammed during flight in 2004.

The acoustical data on the ARU systems were rapidly downloaded for analysis using a USB 2.0 interface. Cornell University software automatically detected sounds of the target species to produce an activity log. Two software packages were developed. One was implemented in Matlab, to facilitate rapid development and testing of new ideas. This system is called XBAT, and it has been released as an open source project (www.xbat.org). The second system was implemented as part of Raven, a Java software product whose initial development was funded by NSF (www.birds.cornell.edu/brp/raven/Raven.html). Raven is simpler to own and operate; XBAT provides a fertile environment for algorithm development, diagnosis, and evaluation. Multiple detector algorithms were implemented, including generalized energy and spectrogram

template correlation routines. The detection log was utilized to automatically extract measurements from the detected sounds, including the location of the sound when an array of microphones had been used.

Table 1: Schedule of field research at Fort Hood

Begin	End	Study Sites
21 March 2001	25 April 2001	Training Area 7b
1 April 2002	10 June 2002	Training Areas 2, 5b, 44b
28 Feb 2003	19 Jul 2003	Training Areas 4a, 5b, Live Fire Area (balloon flights)
2 May 2004	28 May 2004	Live Fire Area (balloon flights)

Results and Discussion

Ground-based recording

Focal recording

Focal recordings of singing BCVI and GCWA were obtained using directional microphones during the 2001 and 2002 field seasons. All of Jeff Bolsinger's recordings, which are housed at the Cornell Lab of Ornithology's Macaulay Library, were digitized and associated metadata were prepared for detector development.

Array recording

Array recordings were utilized to document singing rates for several birds in relation to date and time of day. In 2001 a six-channel array was deployed for five days of recording at the site in east Fort Hood where BCVI were rediscovered in the late 1980s (Training Area 7b). The density of breeding birds proved low there, and in 2002 an extensive search was undertaken for a higher density site. A 16-channel array was deployed a few kilometers north and west of the first array for 49 days. These recordings were made with a laptop computer and a 16-channel analog-to-digital PC Card. Custom software enabled scheduled recordings. In 2002 the array was in operation from 17 April to 9 June 2002, and was scheduled to run for 6 hours starting at dawn (06:00 CST for the month of April; 05:30 CST for the rest of the season). Weather conditions, equipment failures and regular maintenance interrupted some scheduled sessions. Additional recordings were obtained opportunistically, adding some afternoon and evening sessions to the recording set. Table 2 shows the number of hours of recordings made in 2002 for each of the array configurations.

Table 2: Array Recording Summary

Year, Training Area	Channels	Hours
2001, 7B	6	30
2002, 5B	16	434
2003, 5B	22	238
2003, 4B	14	264

Figure 1 illustrates the tripods and microphone fairings that were utilized in 2001 and 2002. This design utilized inexpensive PVC components to provide a stable platform for the microphone approximately 2 m above the ground. This height was above most of the dense vegetation, and greater detection range was realized. To reduce flow noise, a cylindrical fairing was placed around the microphone; it was approximately 20 cm in diameter and utilized a synthetic fur with filaments that were approximately 4 cm long.

Figure 1: Microphone stands and fairings used with the cabled array in the “Dante's Forest” study area in Training Area 4A

ARU hardware

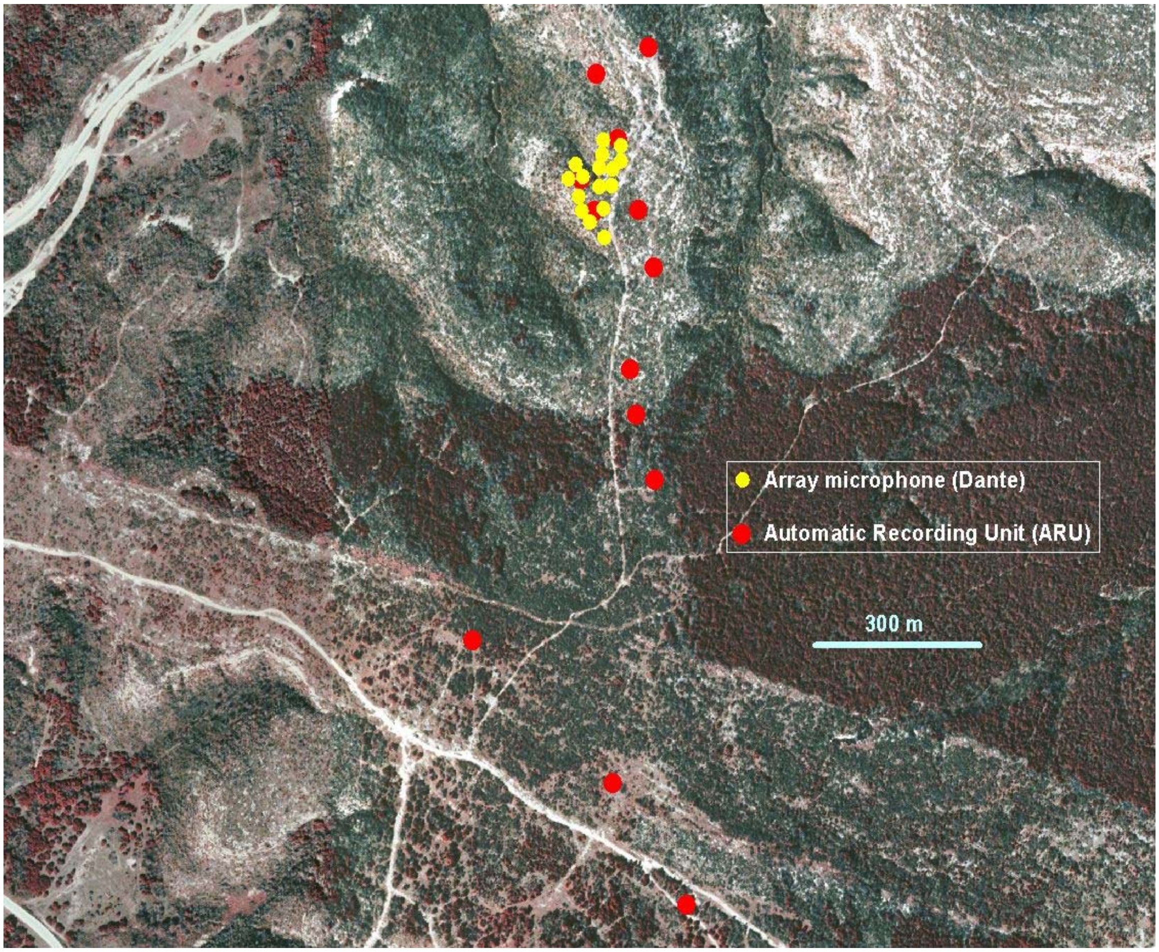
The initial ARU system utilized a Tattletale 8 microcontroller coupled with a hard disk interface board designed and built at Cornell. This system enabled scheduled recordings, conserving

battery and hard disk capacity by turning the system off during portions of the day with low singing rates. In 2002 the ARU hardware was modified to record up to 8 channels of data, and the maximum aggregate sampling rate was increased to 62 kHz. A mechanical redesign replaced elastomeric “squishy bus” connectors with standard 0.1” pin header connections, for a more robust and reliable mechanical package. The ARU was also modified to collect time stamp and positional information from an integrated GPS module, to enable data fusion (spatial registration, temporal synchronization) across our entire suite of recording instruments. 23 units were deployed in 2002, 13 near the array recording site in the eastern section of Fort Hood (Figure 2), and 10 on Manning Mountain in the western section of Fort Hood (Figure 3).

The 2002 systems utilized an unconventional approach to recording. A small array of four microphones was sampled at an aggregate rate of 30 kHz. The low pass filters on each microphone were set at 10 kHz. This meant that the signal in each channel was aliased above 3.25 kHz, but this ambiguity could be resolved by processing the four channels collectively. The goal of the approach was to provide bearing vectors to each song while maximally conserving disk space. Although subsequent signal processing proved that the technique worked, this approach was rendered obsolete by advances in disk capacity and the subsequent availability of commercial, off-the-shelf (COTS) digital recorders.

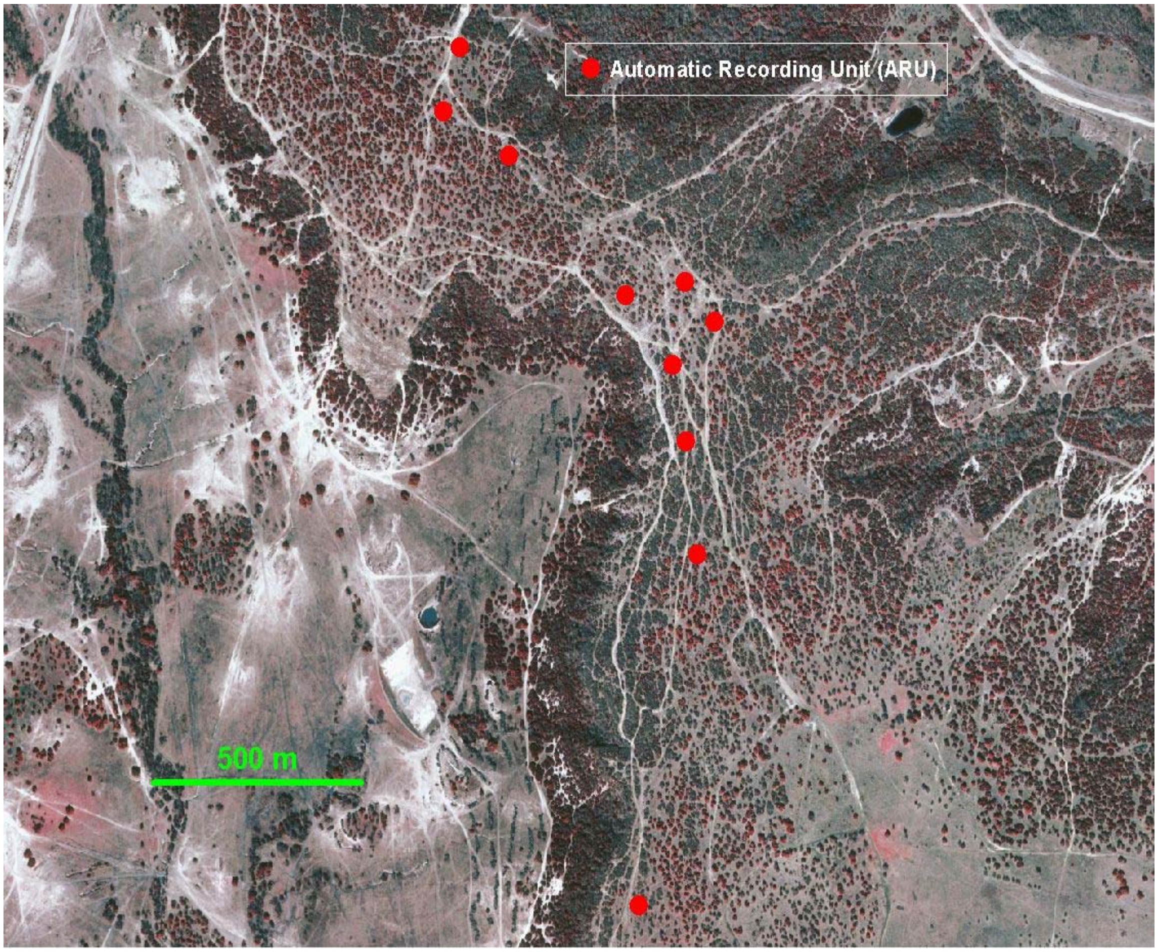
The background of Figure 2 is a composite aerial photo, with a section of the East Range Road appearing at upper left. The mechanically-cleared zone called “Vireo Alley” runs from the middle of the left-hand edge to the lower right corner. The reddish area is GCWA habitat, and the light colored area in the upper right shows the area burned by a crown fire in 1996. The array recording system is indicated in yellow, and the automatic recording systems in red.

Figure 2: BCVI Array and ARU recording locations in 2002



Additional ARU recordings were obtained in 2003, at locations shown in Figure 10.

Figure 3: 2002 BCVI ARUs on Manning Mountain, in the western section of Fort Hood.

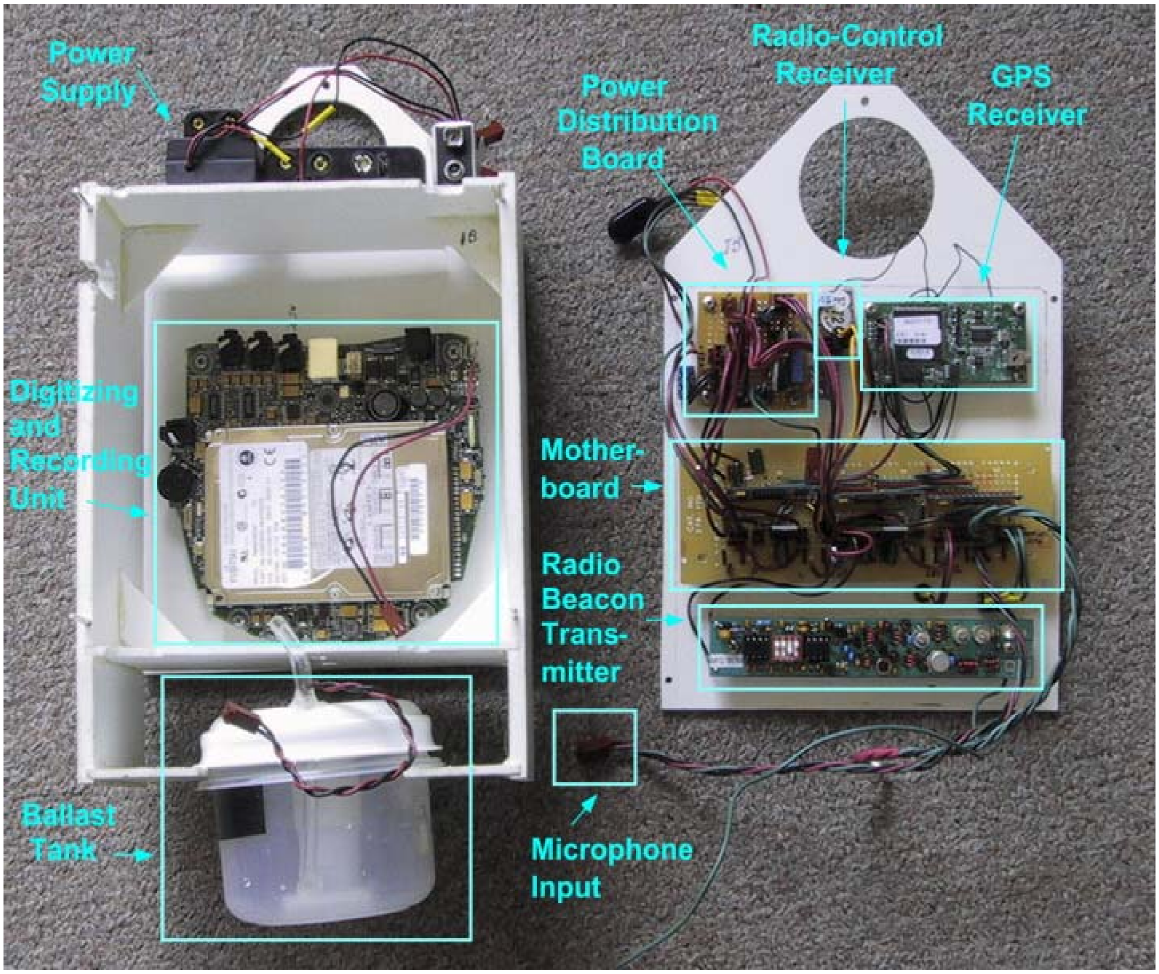


Aerial platform development

Balloon system

The first prototype balloon system was developed in 2001. The command and control system (Figure 4) consisted of three PicStik microcontrollers that were linked by a serial communications bus. One processor controlled the helium valve; one processor monitored the GPS system, and one processor integrated the information and controlled the ballast system.

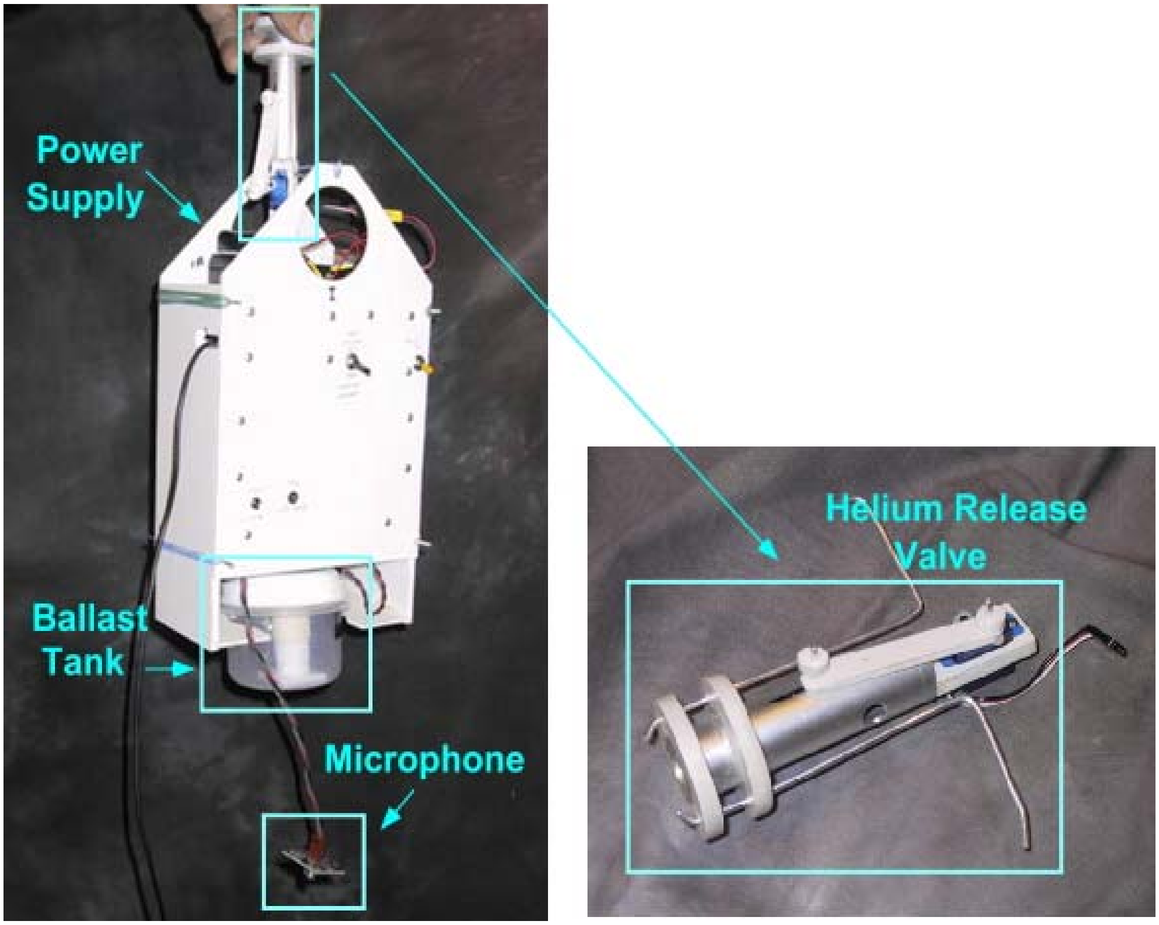
Figure 4: 2002 balloon payload



The ballast system consisted of a small plastic water reservoir, and a COTS, low-power water pump. The GPS subsystem was a Trimble Lassen LP OEM module. No suitable COTS helium valve could be found, so a custom unit was fabricated.

Several features motivated the helium valve design. It had to have very low leakage when closed. It had to have modest power consumption and be lightweight. It needed to fit into the neck of commercial latex weather balloons, and allow topping up of the balloon with helium after attachment. Lastly, it had to have a relatively large opening when venting, to achieve a reasonable flow rate with a small pressure differential. The prototype valve (Figure 5) utilized a miniature servo to drive the valve, with the pulse-width modulation system supplied by a dedicated PIC microcontroller.

Figure 5: 2002 payload and valve



The COTS digital recorder was a Creative Devices Nomad Jukebox. This unit had 6 Gb of recording capacity, which allowed for more than 20 hours of stereo recording at 20 kHz per channel. Sampling rates from 8 kHz to 48 kHz were available. These units enable offloading of data using a USB 1.1 serial connection to a computer. The downloaded acoustic data appear as WAV files in the host computer, ready for immediate review or processing by automatic song detection software.

The balloon system was flown six times at Fort Hood in 2002 (Figure 6). The first two flights were conducted in the presence of a NE wind, and the goal was to conduct a short flight over the middle of the array. The last four flights were conducted in the presence of a southerly wind, and the goal was to conduct longer flights and observe how close to the array the balloon could be made to pass by selecting the appropriate launch point. As the figure indicates, the surface winds did not accurately reflect the direction of the winds at flight altitude. This is especially evident in tracks 3 and 6.

The array recording site is represented by a cluster of yellow dots just below the center of the picture, and the mechanically-cleared path known as “Vireo Alley” is the light colored linear feature that ends in the lower right corner. The balloon flight paths are marked by dots during the

altitude control phases, followed by dashed lines after the descent command was initiated. Track 2 ended meters short of the East Range Road; the area to the west of the road is a live fire area. Tracks 3 and 4 passed over a section of the live fire area.

Figure 6: 2002 balloon flights

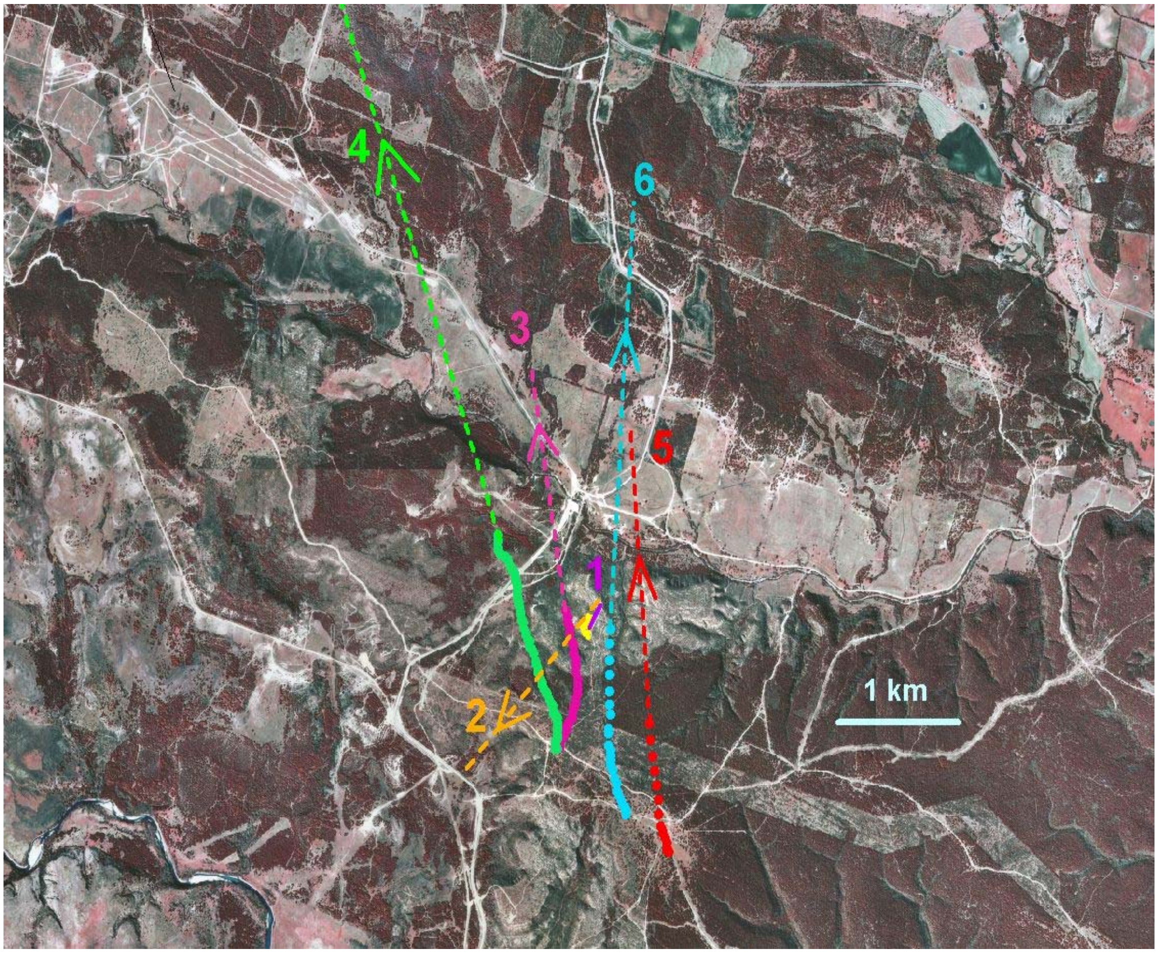


Figure 7 illustrates the altitude tracks of the last four balloon flights. The colored lines represent flight profiles for the last four flights in 2002. The desired altitude was 300 m, and when the balloon exceeded 500 m the onboard computer opened the helium valve to initiate descent. The highest ground elevation along the flight path was 270 m. All of the ascents above 300 m were associated with transit across a 60 m cliff. The prototype altitude control system was unable to compensate for the atmospheric forcing due to atmospheric boundary layer effects.

Table 3 displays numbers of songs of three of the bird species recorded on the flights. Black-capped Vireos and White-eyed Vireos sing very similar songs, so both were logged. Painted Buntings are of special interest; they have declined substantially throughout their range, though populations at Fort Hood seem robust.

Figure 7. Altitude profiles for the last four balloon flights conducted in 2002.

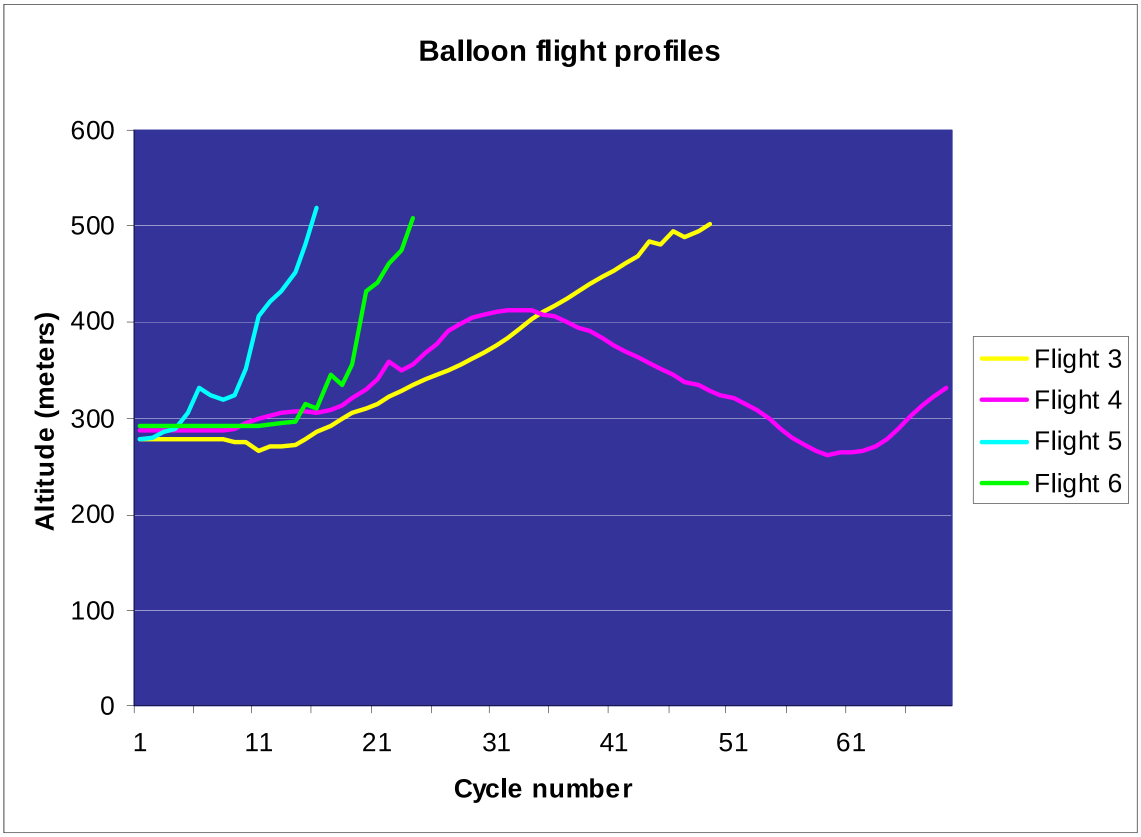


Table 3: Song detections from 2002 flights

Flight number	Total number of Black-capped	Total number of Painted Bunting	Total number of White-eyed Vireo	Total minutes of sample
1	0	1	1	1:20
2	6	23	41	6:00
3	13	16	104	6:00
4	14	14	79	6:00
5	13	30	59	6:00
6	17	28	38	6:00

It was encouraging that roughly the same number of bird songs was detected for two of the three species, even though these flights were conducted on three different days, and at different times of day.

Although the first prototype balloon system functioned adequately, substantial modifications were undertaken to further reduce the size and weight of the system. Three considerations support this priority: economy (less helium used), ease of launching and recovery (smaller size), and avoidance of mandatory flight safety regulation. Lightweight and low-power components were emphasized throughout, and Table 4 illustrates the progress in weight reduction. The two biggest advances were shifting to a COTS recorder that utilized flash memory rather than a hard disk, and elimination of a separate water ballast subsystem. The last iteration of the custom valve system enabled placement of the water ballast inside of the same balloon that held the helium. The water pooled at the base of the balloon, and was vented by an annular opening in the valve seat. A tube at the center of this annular opening served as a snorkel that extended up into the helium gas layer. Different positions of the sliding valve opened the water or helium vents as needed to adjust system buoyancy.

Table 4: Weight reduction of balloon components

Flight Safety Issues	Diameter (m)	Volume (m3)	Payload (kg)	Innovation
CFR 101.1	1.82	3.25	2.71	
2002 Units	1.62	2.23	2.07	
2003 Nomad	1.43	1.54	1.30	Water balloon
2003 Yepp	1.39	1.41	1.16	Flash storage
2004++	1.24	0.99	0.70	Double valve

Diameters and volumes assume 400 g of ballast

Figure 8: Balloon component modifications. The left panel shows the 2002 system being recovered after Flight 5. The balloon, with the valve still attached, is held by Dr. Alejandro Purgue, who later designed the MSP430 controller system and wrote the software. The ballast and control systems are held by Tom Fowler, who designed the entire 2002 system, all subsequent mechanical subsystems, and the wireless communications system for the 2004 balloons. The right panel shows the 2^{nd} generation system during a demonstration in the laboratory. The reservoir and electric pump have been replaced by a water balloon. Note the pair of funnels, which are the horn loaded microphones used for all flights. Tom Fowler (left) is discussing the system with Cornell Bioacoustics Research Program Director Dr. Christopher Clark.

Figure 9: The left panel shows Flight 4 in progress. Rob MacCurdy, who consulted on all aspects of balloon system design, illustrates the difference between the 2003 Nomad and Yepp systems in the right panel just before launch.

In 2003 the balloon control system was ported to a pair of Texas Instruments MSP430 processors. One processor managed all of the hardware, and the other managed the communication and navigation. This revision included software provisions for fully automatic flights. The GPS coordinates of a designated flight area were specified, and the balloon was programmed to automatically descend upon exiting the flight area. The first six flights were conducted in the western quarter of Fort Hood, to take advantage of a more extensive network of roads during test flights. Several software bugs were identified and eliminated in these tests. Table 5 summarizes the balloon flights in 2003 and 2004.

The first 2003 flight (Flight 7), on the north side of Manning Mountain, set an unintentional altitude record (over 3000 meters) because the "polarity" of the water ballast system was reversed. The navigation log enabled us to identify the problem, and implement a software remedy. Unfortunately, the bug fix introduced another problem that caused the control microprocessor reset. Flight 8 resulted in a lost balloon. The balloon was sighted during flight at an appropriate altitude, but it disappeared to the west and extensive searching failed to locate the radio recovery beacon. Flight 9 was a very short test flight, during which the balloon was recovered in spite of this reset problem. The problem was diagnosed and the software was substantially rewritten to trap resets and resume navigation. Flight 10 was another test, and multiple resets were documented in the flight log. These data revealed that a specific command in the altitude regulation mode was triggering the resets, and the software was revised to eliminate this problem. Flight 11 was another short test flight, observed by a local print journalist (Martha Underwood). The winds were light, the drift went exactly as planned, and the balloon landed very near the retrieval vehicle. No software resets were recorded in the record. Flight 12 was a longer test flight. The balloon navigated as expected, and automatically descended to the landing area as programmed.

Flights 13 and 14 were launched on the same morning; these represented the first attempts to fly over the Live Fire Area. Flight 13 landed prematurely because of an incorrect launch parameter. Flight 14 drifted along the eastern edge of the live fire area, landing on the north side of Cowhouse Creek near its entrance to Belton Lake. On the next day, flight 15 followed a similar

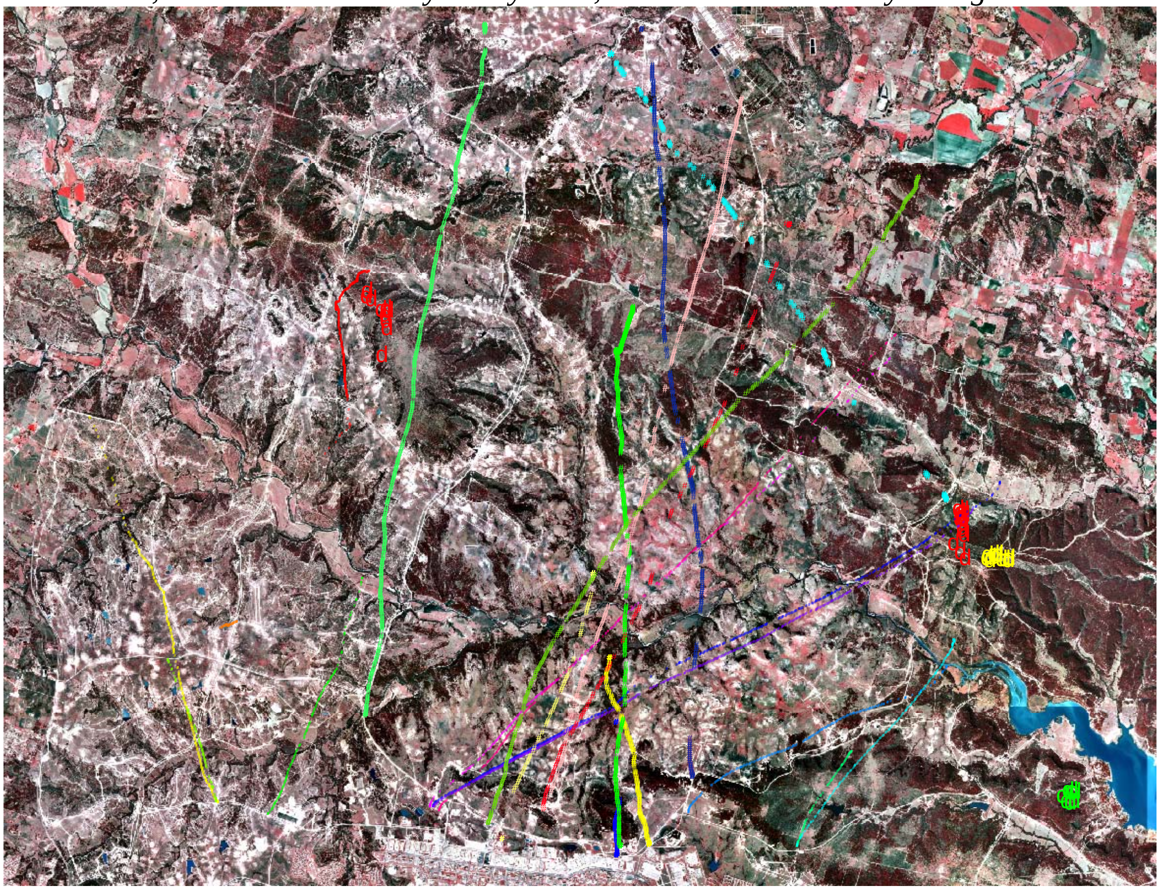
track, landing about 50 meters south of Cowhouse Creek. For all three of these flights, the large balloon drifted on a much more northerly course than our smaller trial balloons had indicated. Flights 16 and 17 were launched near the southwest corner of the Live Fire Area, and drifted east southeast towards the “Vireo Alley” in Training Area 5B. Flights 18 and 19 were launched from the same location, but followed more northerly tracks and landed near the edge of the base. All four of these flights descended automatically upon exiting the flight area, and the units were readily located and recovered by homing in on the radio beacon.

Table 5: Summary of all balloon flights.

Flight #	Date	Duration in minutes	Distance in kilometers	Average speed in m/s	Notes
1	05/30/2002		0.20		
2	05/30/2002		2.00		
3	06/02/2002		3.30		
4	06/02/2002		40.00		CPU malfunction
5	06/04/2002		3.20		
6	06/04/2002		4.70		
7	06/27/2003	41.90	5.55	2.21	ballast malfunction
8	06/28/2003	lost			CPU malfunction
9	07/01/2003	2.50	0.52	3.44	CPU malfunction
10	07/06/2003	25.72	12.01	7.78	
11	07/08/2003	15.62	4.42	4.72	
12	07/09/2003	15.68	7.50	7.97	
13	07/10/2003	8.50	3.21	6.30	bad flight parameters
14	07/10/2003	12.65	7.66	10.09	
15	07/11/2003	19.17	8.77	7.62	
16	07/12/2003	41.37	19.35	7.80	
17	07/12/2003	38.67	18.23	7.86	
18	07/13/2003	36.67	19.01	8.64	
19	07/13/2003	38.42	19.51	8.46	
20	05/04/2004	28.68	20.98	12.19	lost

Flight #	Date	Duration in minutes	Distance in kilometers	Average speed in m/s	Notes
21	05/09/2004	58.90	28.70	8.12	lost
22	05/15/2004	59.73	12.54	3.5	
23	05/16/2004	50.07	17.07	5.68	
24	05/17/2004	14.15	5.78	6.81	
25	05/18/2004	47.43	22.85	8.03	
26	05/19/2004	11.42	4.02	5.86	
27	05/21/2004	41.58	22.45	9	
28	05/24/2004	35.83	14.88	6.92	
29	05/25/2004	71.32	19	4.44	fragmented audio
30	05/25/2004	40.03	22.15	9.22	
31	05/26/2004	11.5	8.49	12.3	
32	05/27/2004	30.48	23.58	12.89	
33	05/27/2004	57.85	20.85	6.01	no audio
all	flights	855.84	422.46	7.46	

Figure 10: Balloon flights and array recording stations for 2003 and 2004. Array recording stations are marked by the letter "d" (red, yellow, or green). 2002 BCVI recording arrays are in red; the 2003 BCVI array is in yellow; the 2003 GCWA array is in green.



Flight 7 (2003): small red symbols	Flight 14 (2003): small aqua symbols
Flight 9 (2003): small orange symbols	Flight 15 (2003): small periwinkle blue symbols
Flight 10 (2003): small yellow symbols	Flight 16 (2003): small royal blue symbols
Flight 11 (2003): small light green symbol	Flight 17 (2003): small purple symbols
Flight 12 (2003): small dark green symbols	Flight 18 (2003): small pink symbols
Flight 13 (2003): small blue-green symbols	Flight 19 (2003): small magenta symbols
Flight 22 (2004): not plotted	Flight 28 (2004): large bright green symbols
Flight 23 (2004): large aqua symbols	Flight 29 (2004): large pink symbols
Flight 24 (2004): large bright yellow symbols	Flight 30 (2004): large red symbols
Flight 25 (2004): not plotted	Flight 31 (2004): large pale yellow symbols
Flight 26 (2004): large royal blue symbols	Flight 32 (2004): large olive green symbols
Flight 27 (2004): large dark blue symbols	Flight 33 (2004): large light green symbols

The first two balloons flown in the 2004 season were lost. Flight 20 landed fairly close to the range road on the northeast edge of the live fire area, and two sets of radio beacon bearings were obtained from the road before the transmitter abruptly ceased transmitting. The next few days were spent searching for the balloon, during periods when the training area was not in use. It was not found. Flight 21 flew much higher than the programmed altitude, and landed well outside the boundary of the installation. No radio beacon signals were detected, but telemetry received near the end of the flight gave good clues to the landing area. The balloon was seen near the ground by a police officer, but an extensive search of the area proved fruitless.

These failures provoked two significant upgrades to the remaining balloon system. The software for the telemetry system was improved to enable bidirectional communications, and an efficient method of translating the telemetry for plotting in a mapping program was developed. With these new features in place, the remaining balloon system was flown and recovered 12 times. The remaining failure mode was premature landings on flights 24, 26, 28, and 31. In all four cases, the balloon control system vented too much helium as the balloon was being lifted by winds over the line of hills along the south end of the live fire area (Blackwell Mountains, Jackson Knob, Black Mountain). The water ballast was empty in all four cases, indicating that the balloon system had exhausted its capacity to restore neutral buoyancy. As a temporary measure, additional water was used in the latter two flights, which enabled the balloon to drift farther. The telemetry system provided accurate locations for the downed balloon and it was recovered as soon as the training range became inactive.

There were eight flights that landed as programmed, and flight operations became routine enough that the balloon was recovered and flown a second time on two days (5/25 and 5/27). However, audio recorder malfunctions occurred on flights 30 and 33, so no bird survey data could be extracted. Flight 33 was noteworthy because it drifted in an unexpected direction, and would have automatically landed very shortly after launch if we had not used the telemetry system to abort the landing and keep the balloon in the air.

Bidirectional telemetry and the capacity to overlay balloon and recovery vehicle positions on a digital map provided dramatic increases in control and reliability for the balloon system. The altitude control algorithm needs to be modified to account for the effects of wind over mountain ridges. The current system mistakenly tries to dump enough helium to prevent the balloon from climbing. The software will need to be revised to sense these terrain effects, and suspend efforts to maintain altitude under these conditions. It would also be advantageous to accelerate the descent phase of the flight by venting helium more rapidly. This would allow the balloon to land much closer to the programmed boundary of the flight area. This will require a new valve having a larger diameter vent.

Table 6 documents the species of birds that were identified from sounds recorded during the 2004 flights. These are ordered by Partners in Flight (PIF) Bird Conservation Scores (BCS), which index the priority attached to efforts to conserve each species. Note that species with loud songs at lower frequencies (Northern Bobwhite, American Crow) were disproportionately detected because their sounds were audible at much longer ranges than sounds from smaller songbirds.

Table 6: Species detected acoustically during one or more balloon flights at Fort Hood, sorted by Partners in Flight (PIF) bird conservation score (BCS). Higher BCS value indicates higher conservation priority.

Species heard during flight	**PIF BCS**	**# Flts**	**Species heard during flight**	**PIF BCS**	**# Flts**
Golden-cheeked Warbler: GCWA	35	5	Yellow Warbler?	18	1
Black-capped Vireo: BCVI	33	9	Blue Grosbeak	17	6
Painted Bunting: PABU	28	10	Red-bellied Woodpecker	17	3
Bell's Vireo: BEVI	26	6	White-eyed Vireo	16	10
Scissor-tailed Flycatcher: STFL	25	4	Tufted Titmouse	16	5
Rufous-crowned Sparrow: RCSP	24	4	Black-and-white Warbler	16	3
Dickcissel: DICK	23	10	Carolina Wren	15	10
Northern Bobwhite	22	10	Northern Mockingbird	15	10
Wild Turkey	21	4	Red-eyed Vireo	15	3
Field Sparrow: FISP	21	3	Indigo Bunting	14	8
Canyon Wren	21	1	Mourning Dove	14	5
Chimney Swift	21	1	Red-winged Blackbird	14	5
Lark Sparrow: LASP	21	1	Brown-headed Cowbird	14	2
Bewick's Wren	20	9	Common Yellowthroat?	14	1
Carolina Chickadee	20	9	Great Blue Heron?	14	2
Eastern Meadowlark	20	7	Northern Cardinal	13	10
Yellow-billed Cuckoo: YBCU	20	5	Blue Jay	13	2
Summer Tanager	20	4	Great-tailed Grackle	13	2
Red-headed Woodpecker	20	1	Cedar Waxwing?	13	1
Killdeer	19	8	American Crow	12	10
Great-crested Flycatcher	19	4	Blue-gray Gnatcatcher	12	10
Common Nighthawk	19	1	House Finch	12	1
Greater Roadrunner	19	1	European Starling	10	1
Yellow-breasted Chat	18	7	Duck sp.		1
Grasshopper Sparrow: GRSP	18	2	Magnolia Warbler		1
			Spotted Towhee?		1

Table 7 documents the number of songs detected for eleven species of birds that were selected for more detailed analysis: six species with the highest BCS scores, additional sparrows, and the Yellow-billed Cuckoo (a rarely detected bird with a low-pitched call). Estimates are included for the number of birds responsible for these calls. These estimates use a simple cue-counting

method. The average number of songs detected per bird is estimated from the average track distance over which songs can be heard, the average flight speed, and the average song interval for the species. The formula used was:

mean songs per bird =
distance heard (m/bird) / flight speed (m/s) / song interval (s/song)

Total numbers of birds detected across flights are not presented, because it is clear from the maps (Figures 11 to 15) that many birds were counted more than once.

Table 7: Numbers of songs, and estimated numbers of birds detected for selected species detected during balloon flights over Fort Hood. See main text for explanation of bird estimation procedure.

2004 Flight #	Average flight speed	Species	BCVI	BEVI	DICK	FISP	GCWA	GRSP	LASP	PABU	RCSP	STFL	UNKN	YBCU	TOTAL
		Seconds per song	3.2	4.1	4.5	11.77	11.77	11.77	11.77	6.2	11.77	2.4			
		Average track distance per bird in meters	150	150	200	200	200	200	200	200	200	200			
22	3.5	songs	114	11	11	22	55	0	0	290	4	2	4	0	513
		birds	***9***	***2***	***1***	***5***	***12***	***0***	***0***	***32***	***1***	***1***		***0***	**63**
23	5.68	songs	132	0	269	1	0	0	0	216	1	0	29	1	649
		birds	***16***	***0***	***35***	***1***	***0***	***0***	***0***	***39***	***1***	***0***		***1***	**93**
24	6.81	songs	20	1	161	0	1	0	0	45	5	1	1	0	235
		birds	***3***	***1***	***25***	***0***	***1***	***0***	***0***	***10***	***3***	***1***		***0***	**44**
25	8.03	songs	6	9	291	2	7	5	0	79	0	4	38	1	442
		birds	***2***	***2***	***53***	***1***	***4***	***3***	***0***	***20***	***0***	***1***		***1***	**87**
26	5.86	songs	1	0	0	0	0	0	1	48	0	0	2	0	52
		birds	***1***	***0***	***0***	***0***	***0***	***0***	***1***	***9***	***0***	***0***		***0***	**11**
27	9	songs	6	0	0	10	22	0	1	40	0	1	2	1	83
		birds	***2***	***0***	***0***	***6***	***12***	***0***	***1***	***12***	***0***	***1***		***1***	**35**
28	6.92	songs	17	12	0	0	6	0	0	91	0	24	2	3	155
		birds	***3***	***3***	***0***	***0***	***3***	***0***	***0***	***20***	***0***	***2***		***1***	**32**
30	9.22	songs	89	8	0	2	20	1	0	82	2	0	9	1	214
		birds	***18***	***3***	***0***	***2***	***11***	***1***	***0***	***24***	***2***	***0***		***1***	**62**
31	12.3	songs	12	0	0	2	0	0	0	39	1	0	2	0	56
		birds	***4***	***0***	***0***	***2***	***0***	***0***	***0***	***15***	***1***	***0***		***0***	**22**
32	12.89	songs	3	10	0	0	0	0	0	67	0	3	6	0	89
		birds	***1***	***4***	***0***	***0***	***0***	***0***	***0***	***27***	***0***	***1***		***0***	**33**

Figures 11 to 15 illustrate bird song detections during the 2004 balloon flights. Segments of the outer boundary of Fort Hood are visible as black lines, and the perimeter range road that outlines the live fire training area is displayed in gray. The start of each flight is marked by an arrow and a number indicating the date in May of the launch. Altitude along the flight path is coded in gray scale. Bird song detections are indicated by circles that code species by color. The two flights that did not yield audio data are included in Figure 11, the all species map, but omitted from subsequent maps.

Figure 11

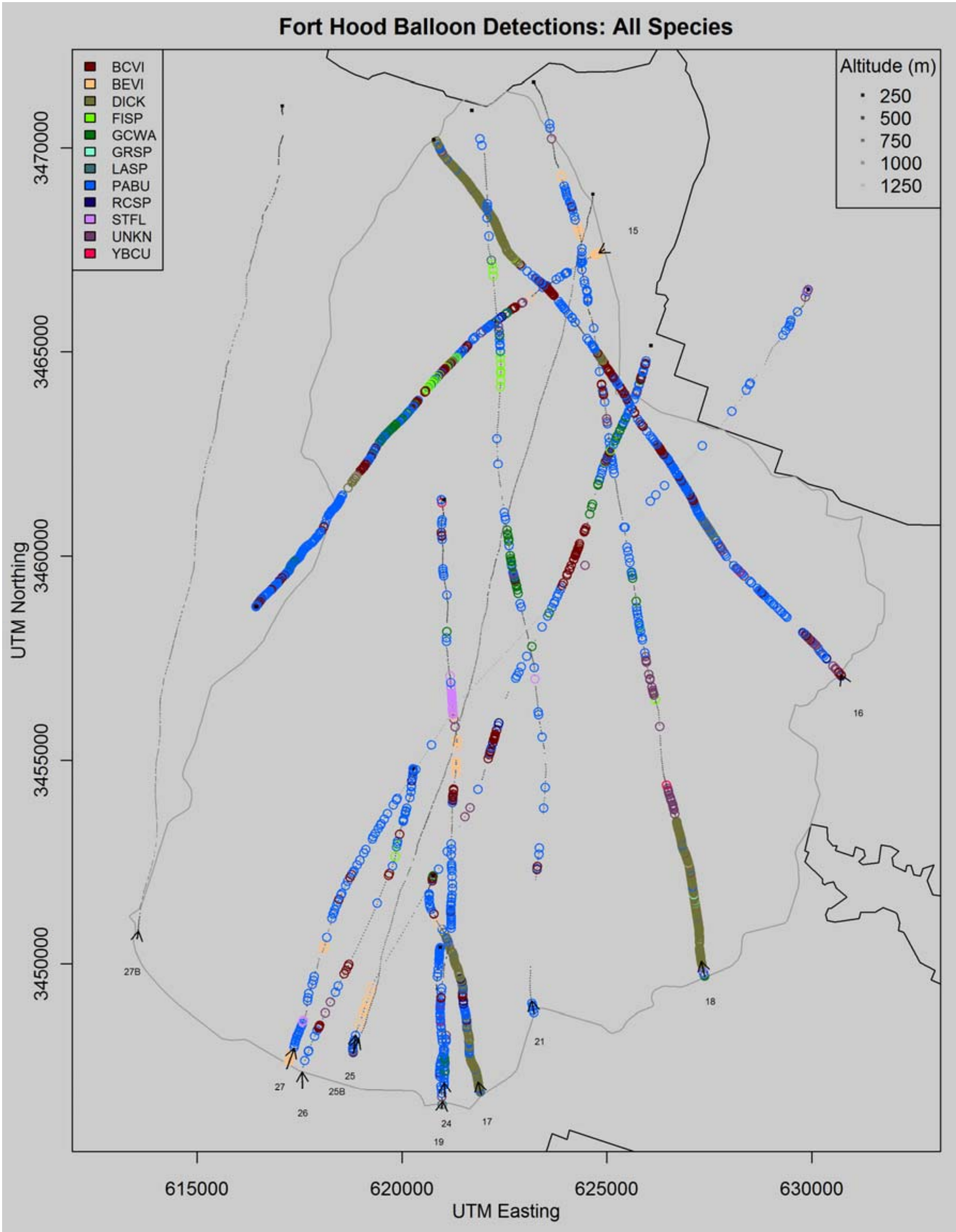

Fort Hood Balloon Detections: All Species
BCVI
BEVI
DICK
FISP
GCWA
GRSP
LASP
PABU
RCSP
STFL
UNKN
YBCU
Altitude (m)
250
500
750
1000
1250
UTM Northing
3470000
3465000
3460000
3455000
3450000
UTM Easting
615000
620000
625000
630000
15
16
18
21
17
24
19
25
25B
26
27
27B

Figure 12

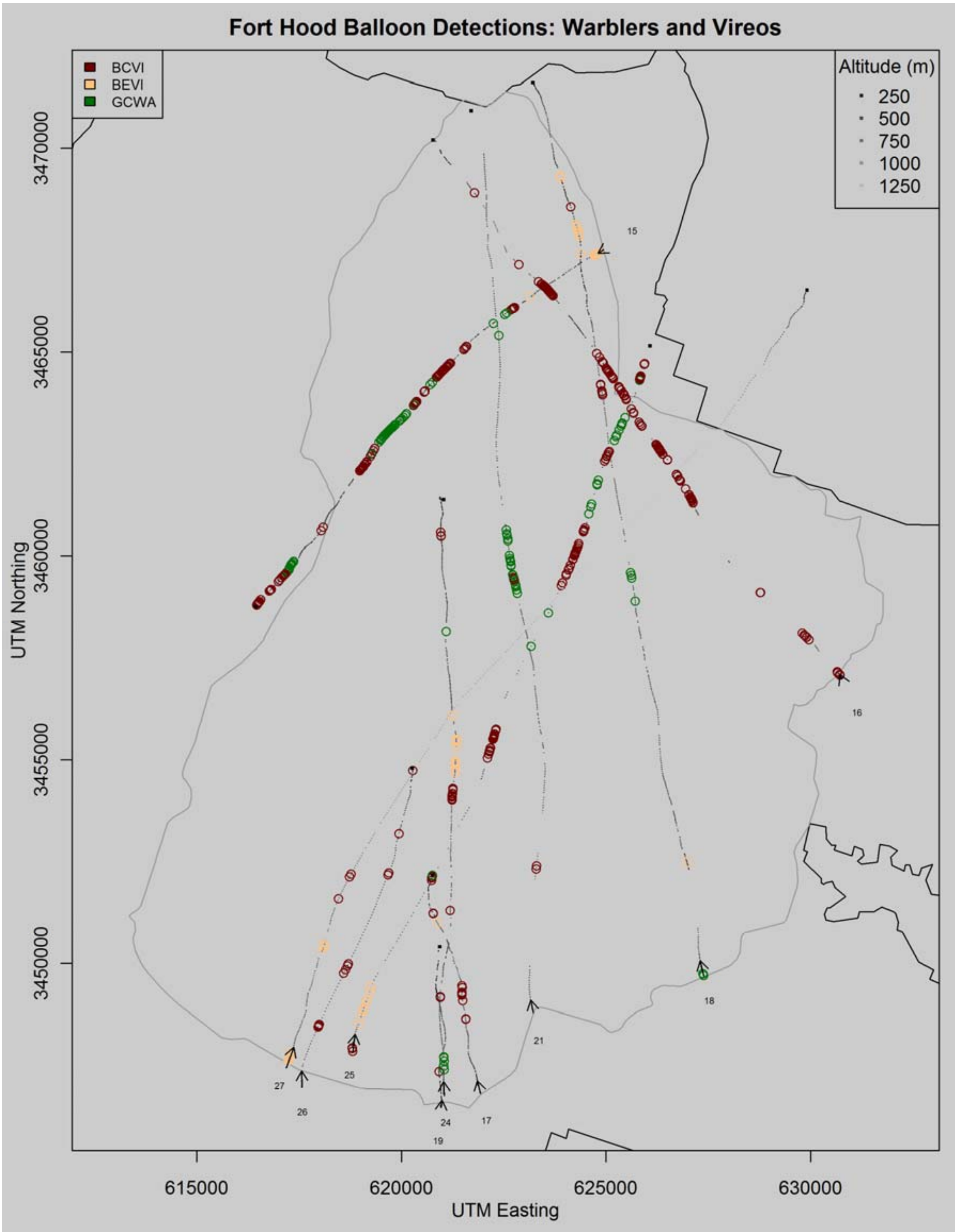
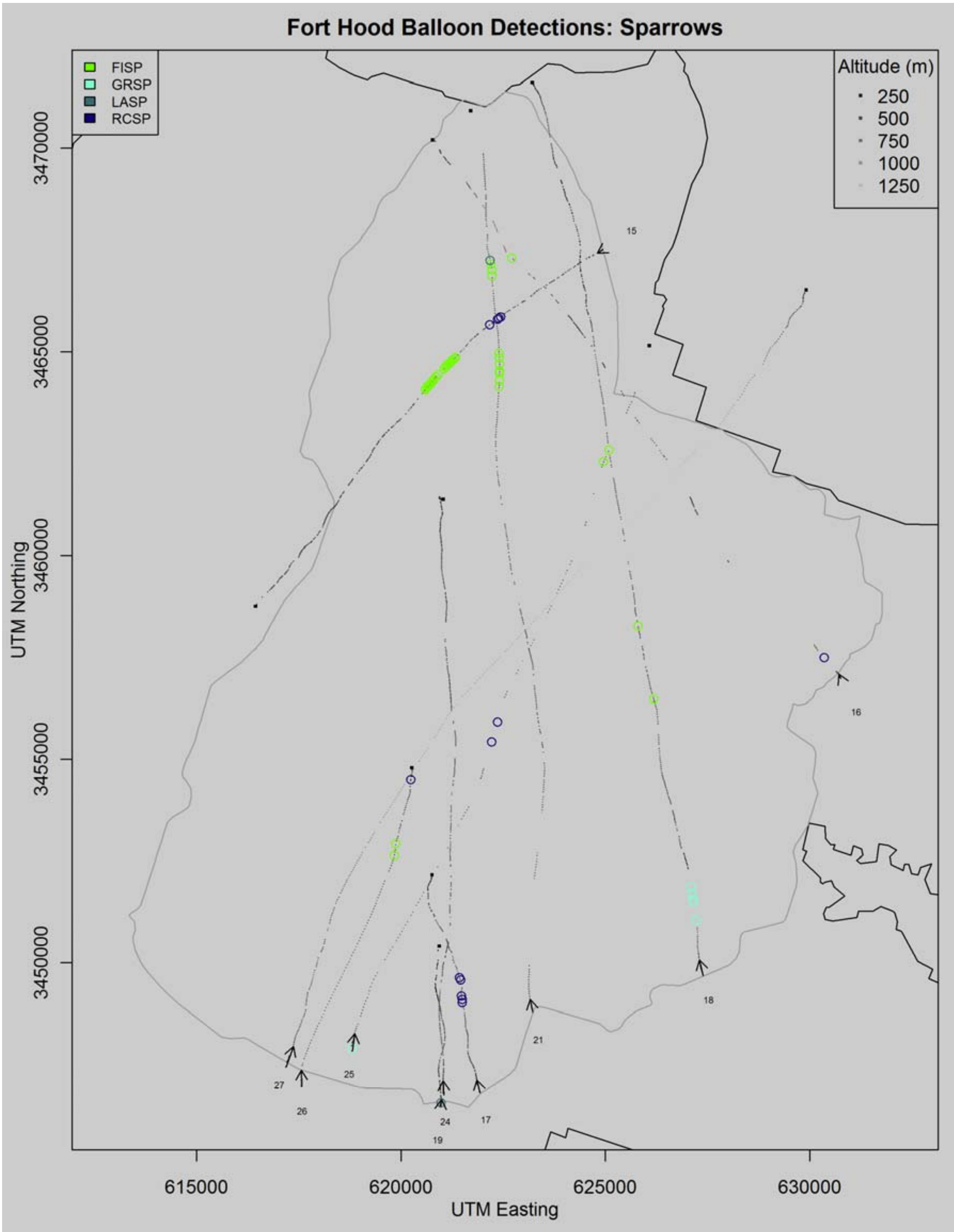

Fort Hood Balloon Detections: Warblers and Vireos
BCVI
BEVI
GCWA
Altitude (m)
250
500
750
1000
1250
UTM Northing
3470000
3465000
3460000
3455000
3450000
UTM Easting
615000
620000
625000
630000
15
16
18
21
17
19
24
25
26
27

Figure 13



Fort Hood Balloon Detections: Sparrows
FISP
GRSP
LASP
RCSP
Altitude (m)
250
500
750
1000
1250
UTM Northing
UTM Easting
3470000
3465000
3460000
3455000
3450000
615000
620000
625000
630000
15
16
18
21
17
24
19
26
27
25

Figure 14

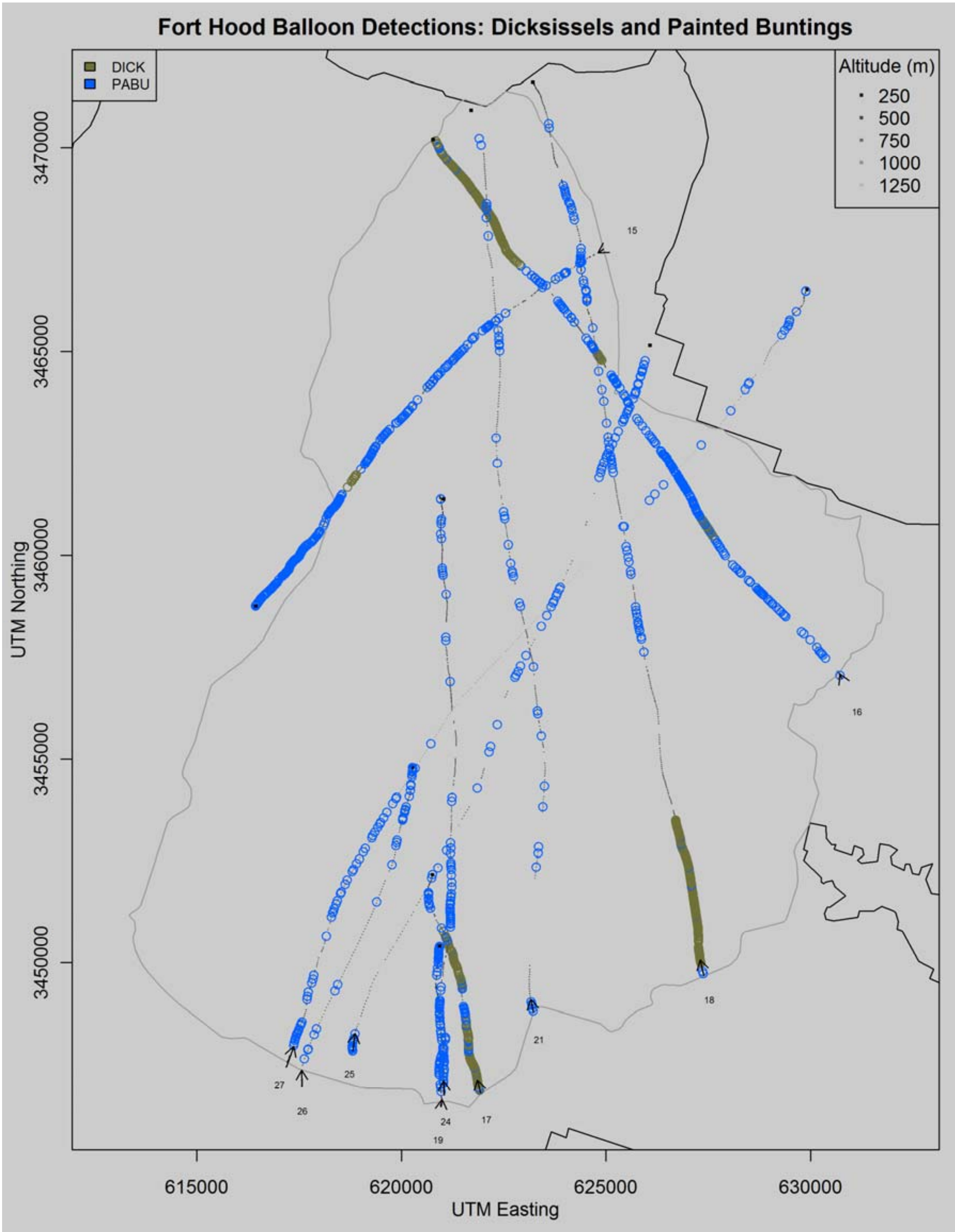
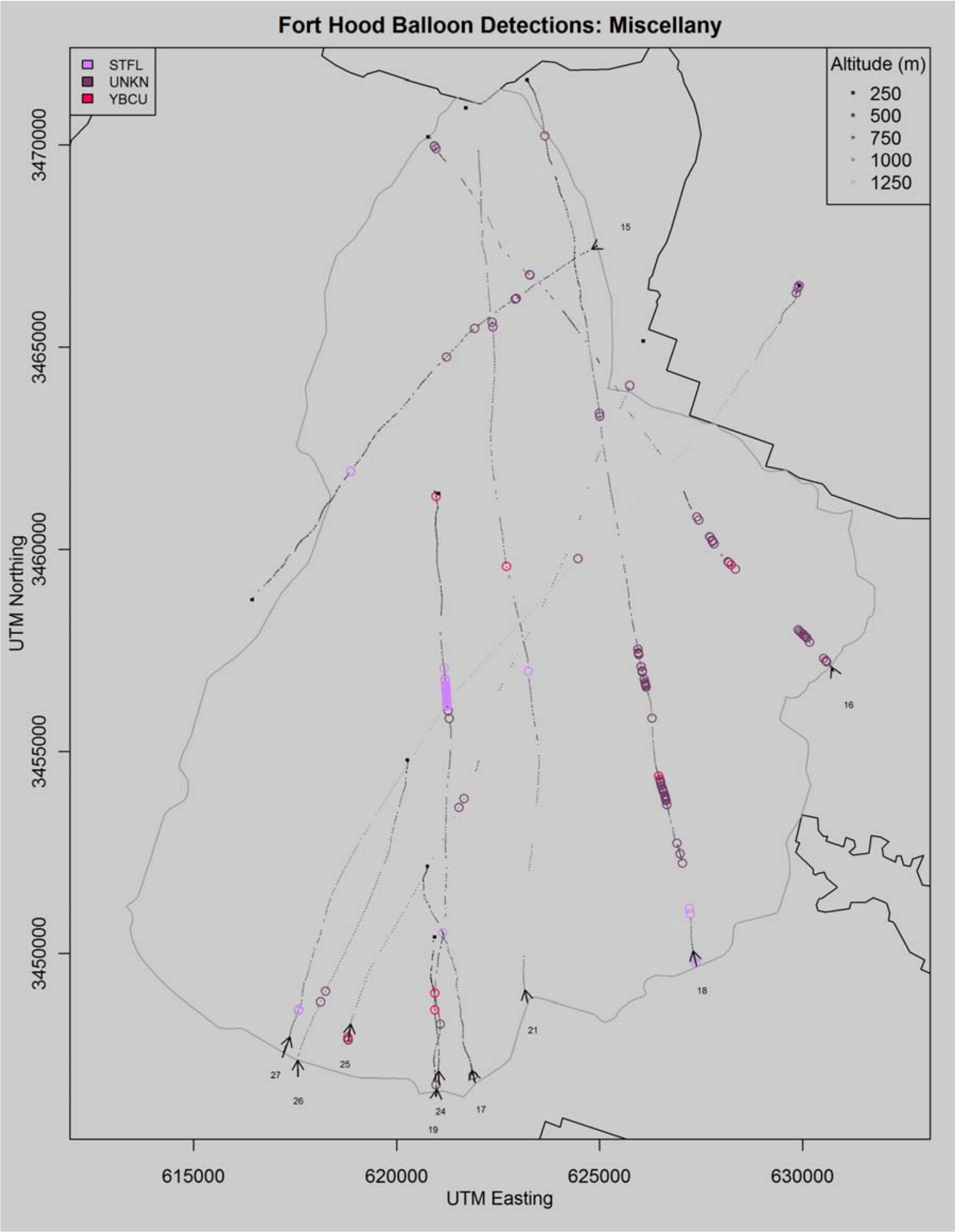

Fort Hood Balloon Detections: Dicksissels and Painted Buntings
DICK
PABU
Altitude (m)
250
500
750
1000
1250
UTM Northing
UTM Easting
3450000
3455000
3460000
3465000
3470000
615000
620000
625000
630000
15
16
17
18
19
21
24
25
26
27

Figure 15



Fort Hood Balloon Detections: Miscellany
STFL
UNKN
YBCU
Altitude (m)
250
500
750
1000
1250
UTM Northing
UTM Easting
3470000
3465000
3460000
3455000
3450000
615000
620000
625000
630000
15
16
17
18
19
21
24
25
26
27

In order to infer the average track distance during which a single bird can be heard, a cluster analysis (single linkage) was performed on the call events on each flight (Everitt, Landau, and Leese. 2001). This yielded clusters of songs for each flight, where the cluster sizes were limited by a maximum interval between songs. Figures 16 through 22 plot the balloon track distance covered during a song cluster, as a function of the maximum song interval used to define the clusters.

Figure 16, Figure 18, Figure 20, and Figure 21 have sufficient numbers of points to exhibit a dense region of cluster lengths that reach a relatively defined asymptote. This dense region was interpreted as coming from a spatially compact group of birds, and the asymptote was taken as the average trackline distance over which songs from that species were audible. Clusters that were audible over much longer segments of track were interpreted as spatially diffuse groups of birds. The values in the second row of Table 7 were drawn from these figures. Groups of species, such as sparrows, were assigned a common value for average track distance for sustained detection.

In order to implement a simple cue counting estimate (Ahlo 1990, Buckland, *et al.* 1994, Huggins 1989, 1991) of the number of singing birds, the average song interval rate of each species was needed. A temporal autocorrelation analysis was performed on the song events. For species whose songs were too sparse to perform an autocorrelation analysis, the modal value for the empirical density function for song intervals was used. Table 8 compares the results of modal song interval values and autocorrelation peak values for nine species of interest. For the common birds, especially Dicksissels and Painted Buntings, the modal density value was less than the autocorrelation peak value, indicating that multiple birds were usually present. Values from this table were used to populate the first row in Table 7.

Table 8: Comparing the modal song interval values and autocorrelation peak values for nine species of interest

Species	Sample size	Peak density (s)	Autocorr peak (s)
BCVI	390	1.6	3.2
BEVI	45	5.5	4.1
DICK	728	0.7	4.5
FISP	33	12.0	11.6
GCWA	105	7.7	9.8
GRSP	4	14.3	
PABU	987	3.9	6.2
RCSP	8	11.2	0
STFL	29	2.6	2.4

Figure 16

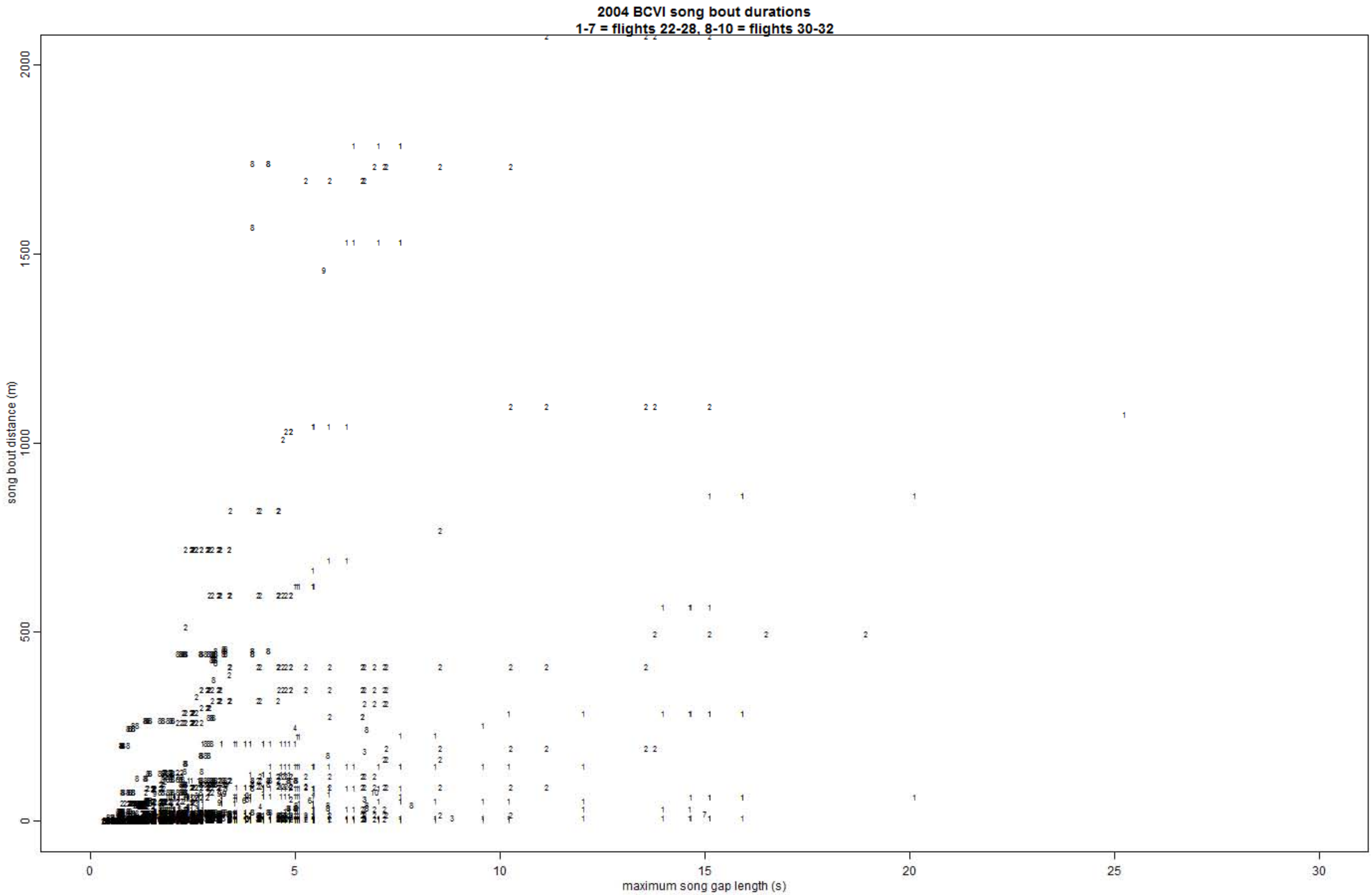
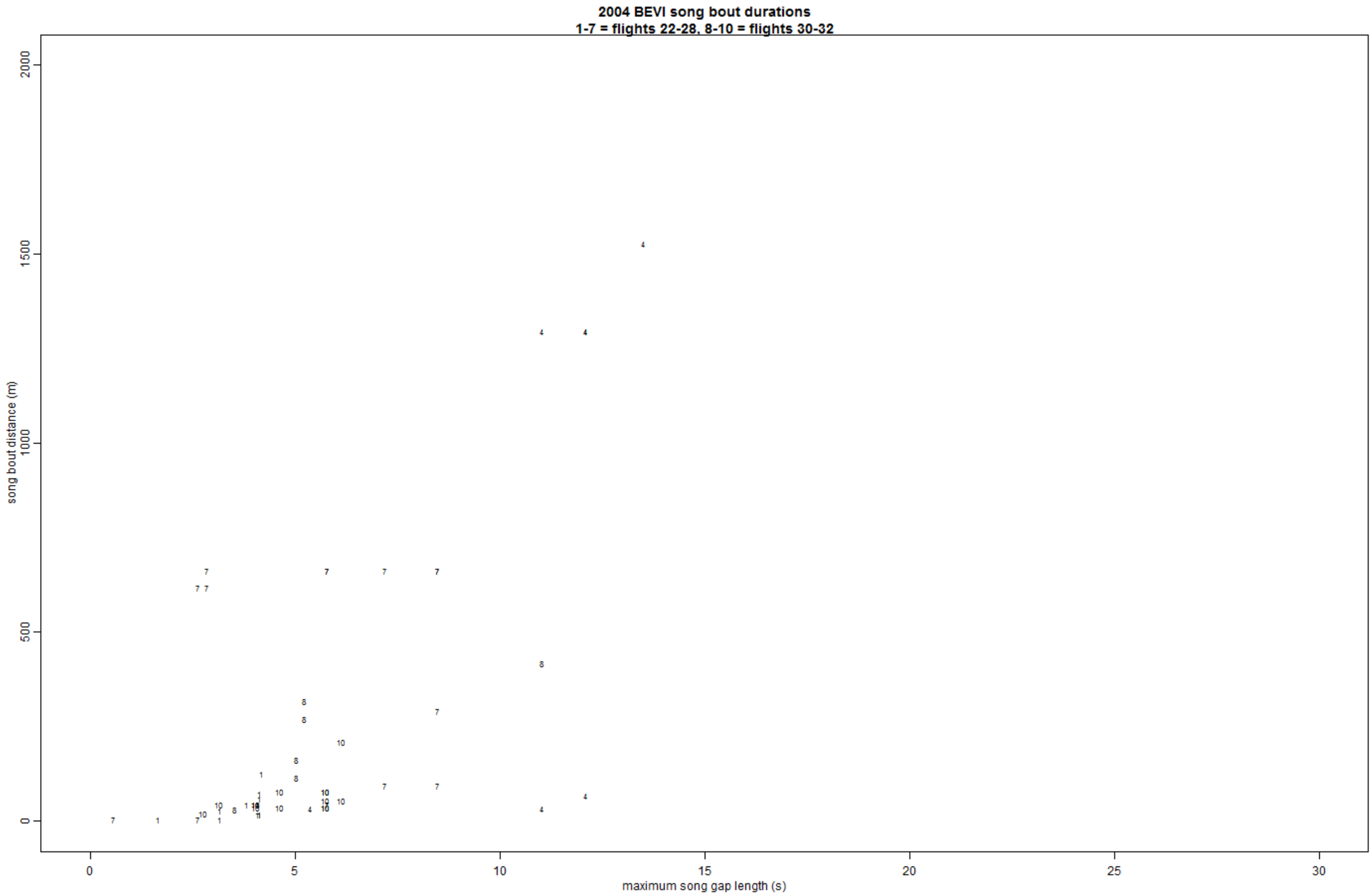

2004 BCVI song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)
0
500
1000
1500
2000
0
5
10
15
20
25
30

Figure 17



2004 BEVI song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)

Figure 18

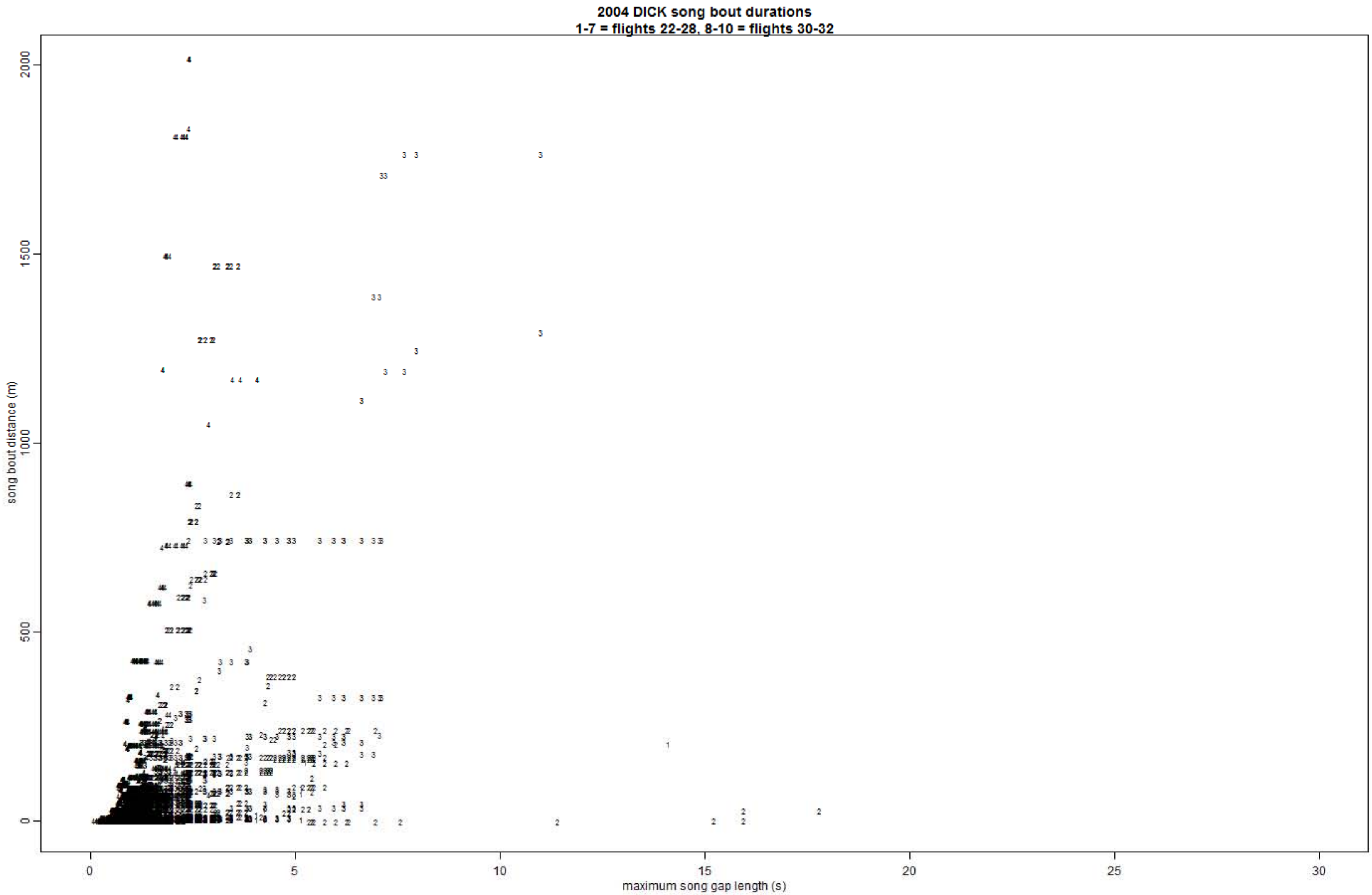
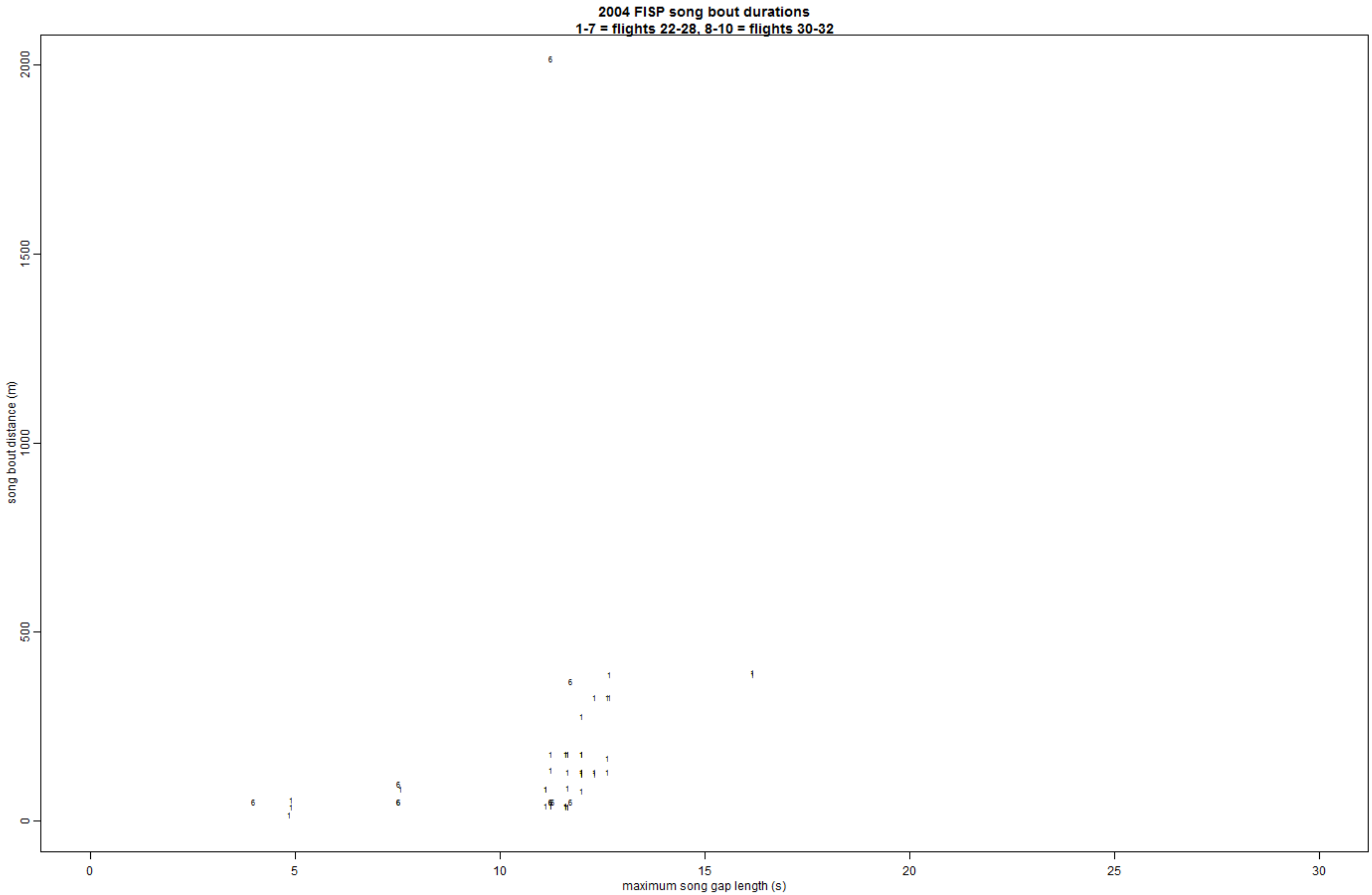

2004 DICK song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)
0
500
1000
1500
2000
0
5
10
15
20
25
30

Figure 19



2004 FISP song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)
0
500
1000
1500
2000
0
5
10
15
20
25
30

Figure 20

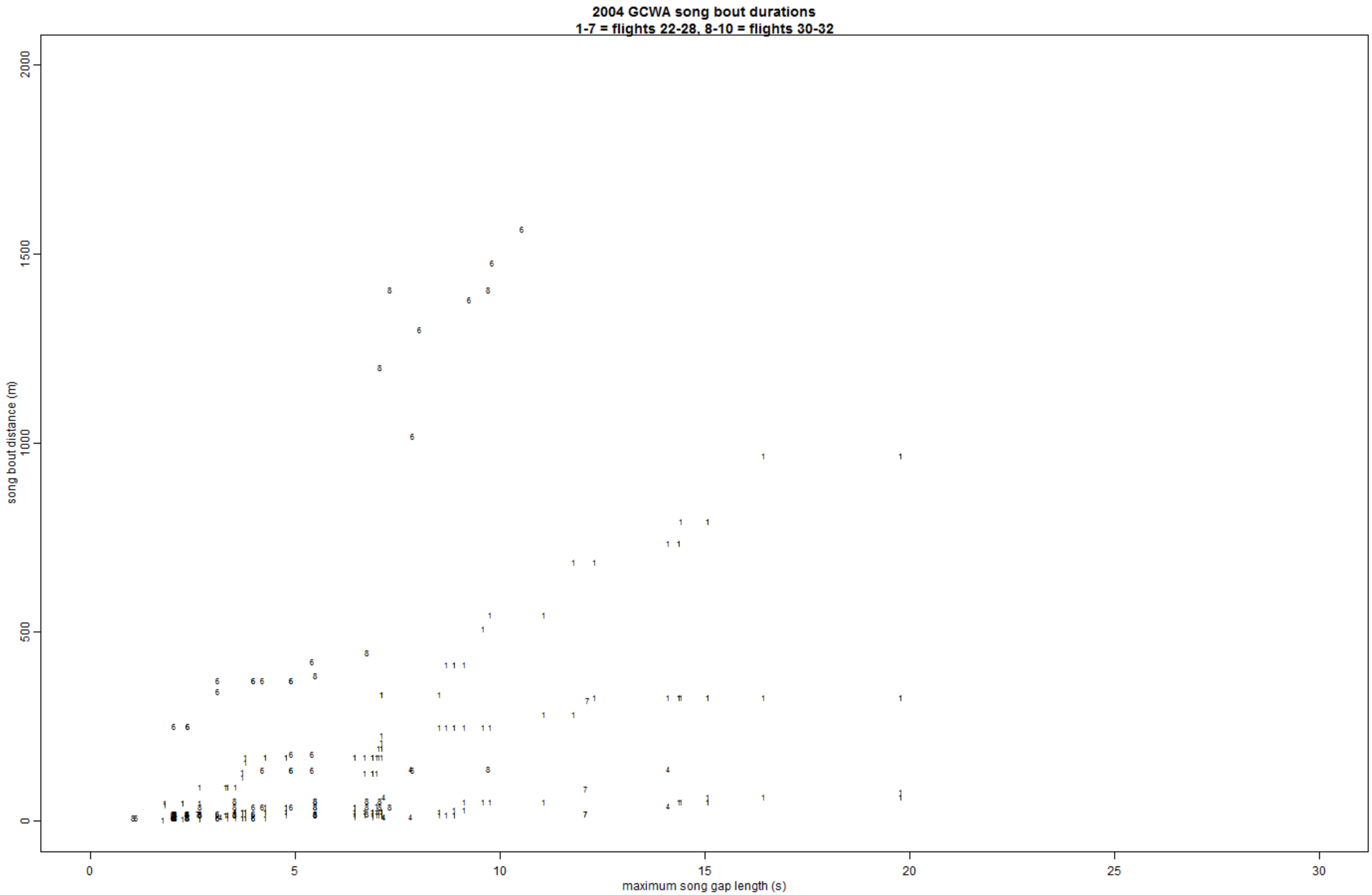
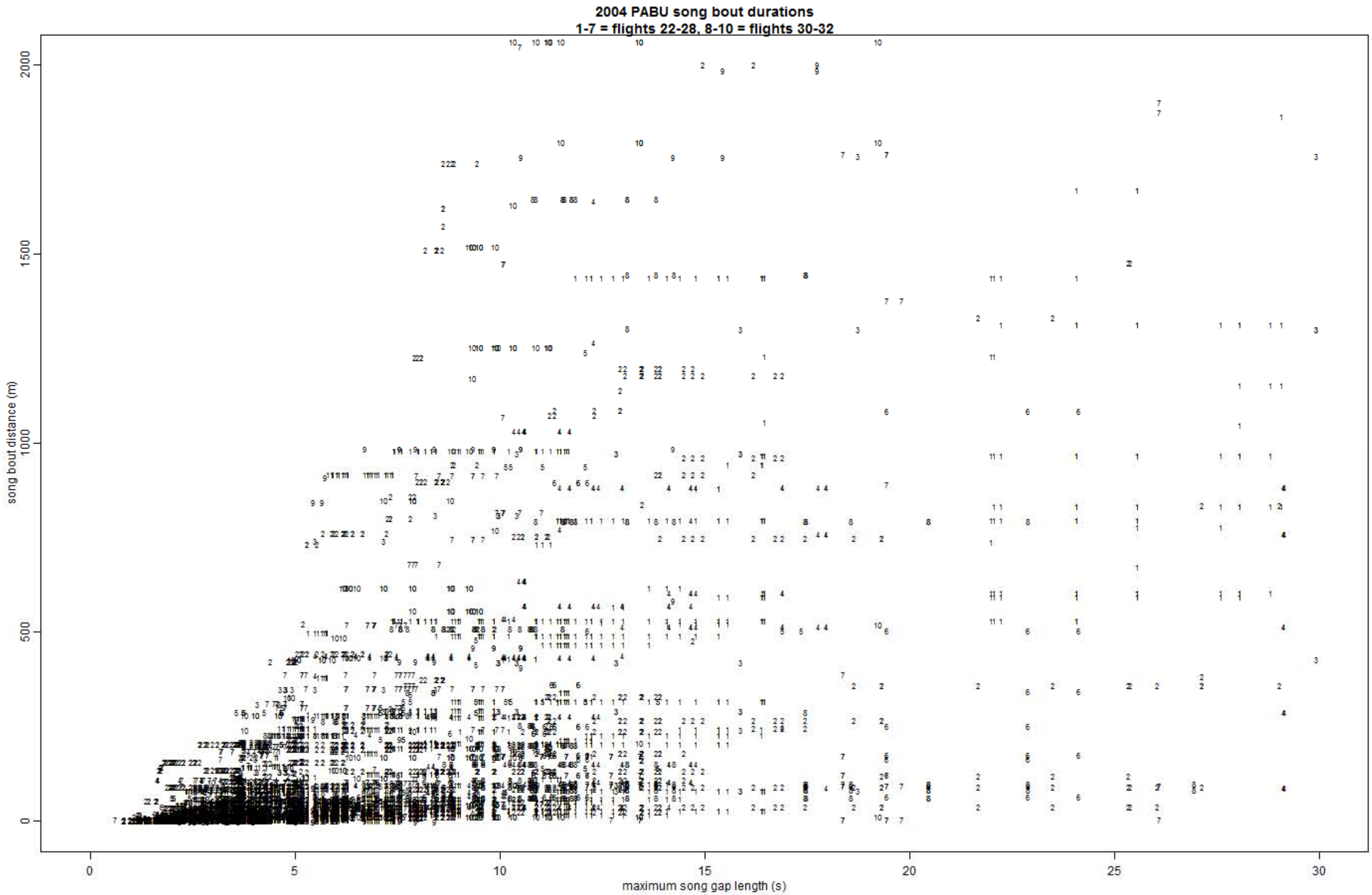
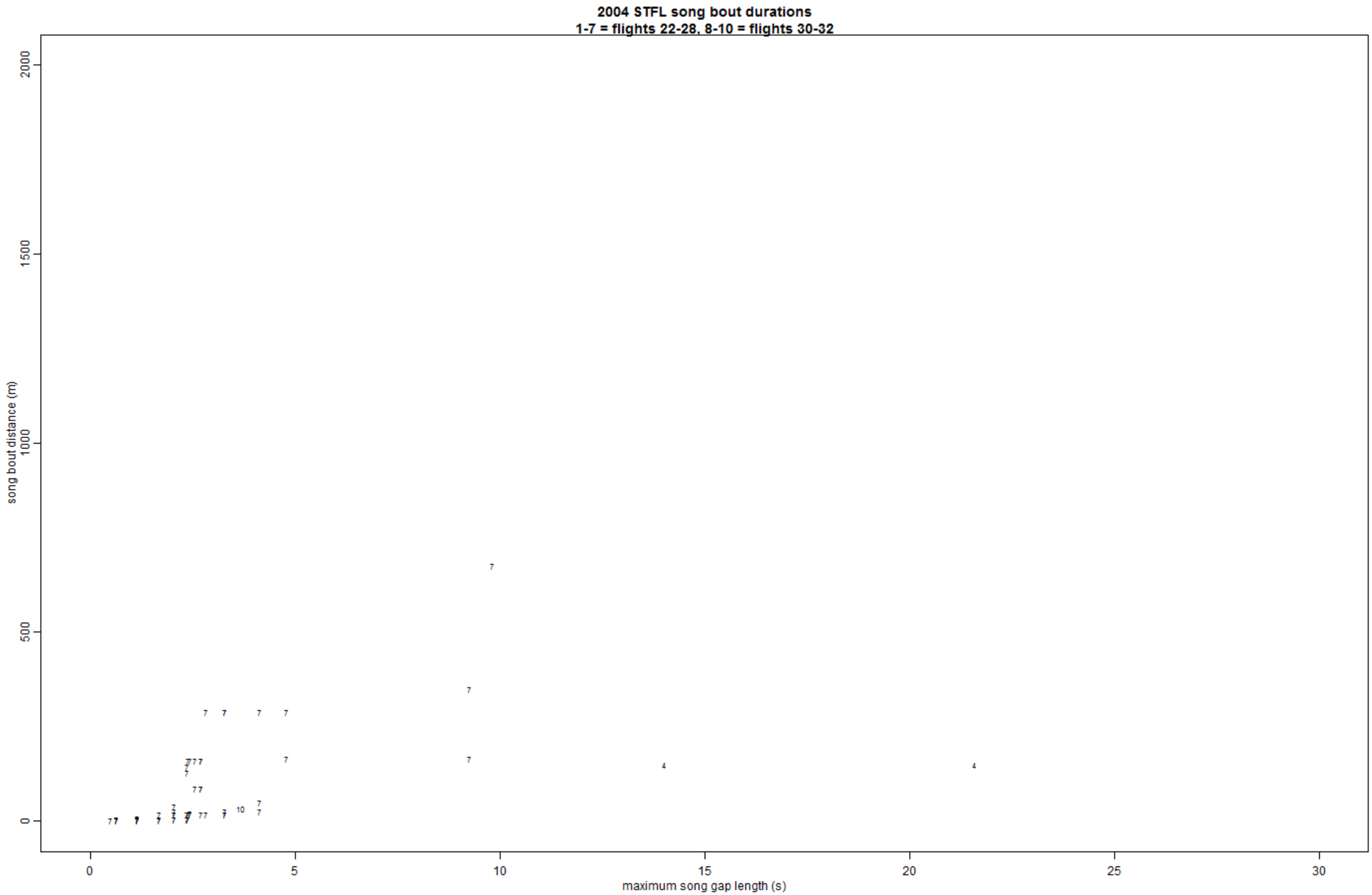

2004 GCWA song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)
0
500
1000
1500
2000
0
5
10
15
20
25
30

Figure 21



2004 PABU song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)
0
500
1000
1500
2000
0
5
10
15
20
25
30

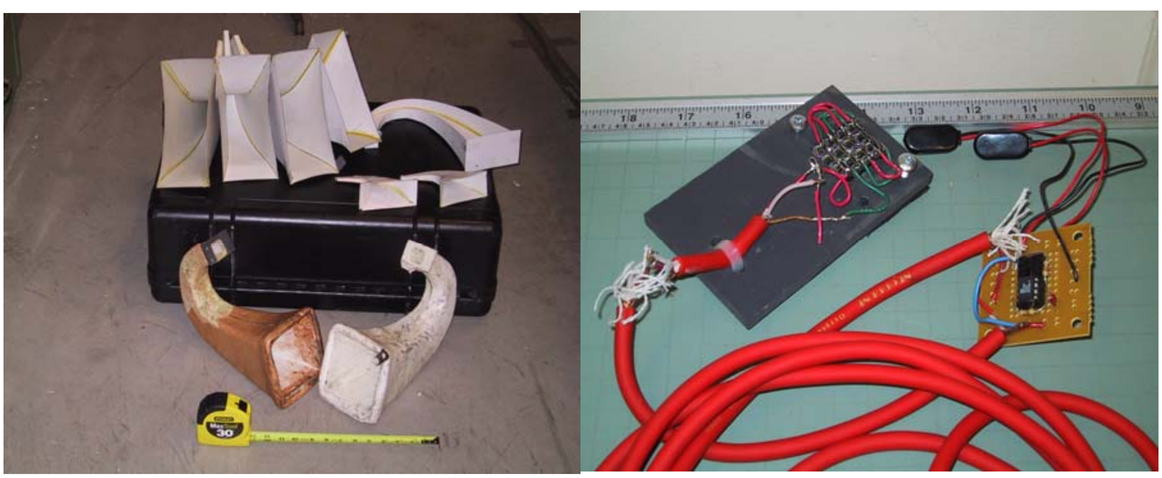
Figure 22


2004 STFL song bout durations
1-7 = flights 22-28, 8-10 = flights 30-32
song bout distance (m)
maximum song gap length (s)

Flight tests in 2002 indicated that balloons would need to drift a few hundred meters above the ground in order to avoid control problems associated with the turbulent boundary layer. This altitude requirement motivated research and development focused on more sensitive microphone systems. This effort included design and fabrication of custom horn systems to physically amplify the sounds reaching the microphone elements. The design parameters for the horns are throat area, flare rate, and mouth area. Analytical models of sound propagation were used in these designs, but the results can be expressed in terms that appeal to acoustical intuition. The ratio of mouth to throat area largely determines the amplification factor. The flare rate determines the low frequency cutoff characteristic of the horn. The directionality of the horn at any frequency can be closely approximated by the performance of a piston transducer of equivalent size and shape.

A variety of horn configurations were designed, fabricated, and tested (Figure 23, left panel). Experimental compound microphones were also fabricated (Figure 23, right panel), to investigate the relationships among cost, power consumption, and performance. Curved horn lenses were tested for terrestrial applications, because they can provide superior protection from precipitation and can potentially be oriented towards the sky for flight call detection. Compound microphones with up to 21 microphones were also evaluated, which offered a 13 dB increase in sensor signal-noise ratio. At the conclusion of these tests, a simple design emerged that offered excellent performance with a good combination of low cost, weight, and power consumption (Figure 8, right panel).

Figure 23. Experimental microphone designs. Left panel: custom horns designed to physically amplify sound. Right panel: compound microphones.



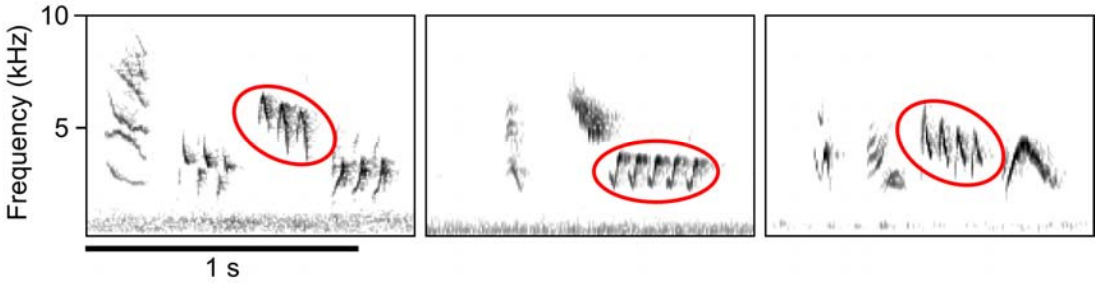
Signal processing algorithms

Automatic detection

BCVI songs include an enormous diversity of notes, perhaps exceeding100 distinct kinds of notes. However, all notes are narrowband, frequency modulated signals. A consistent feature of

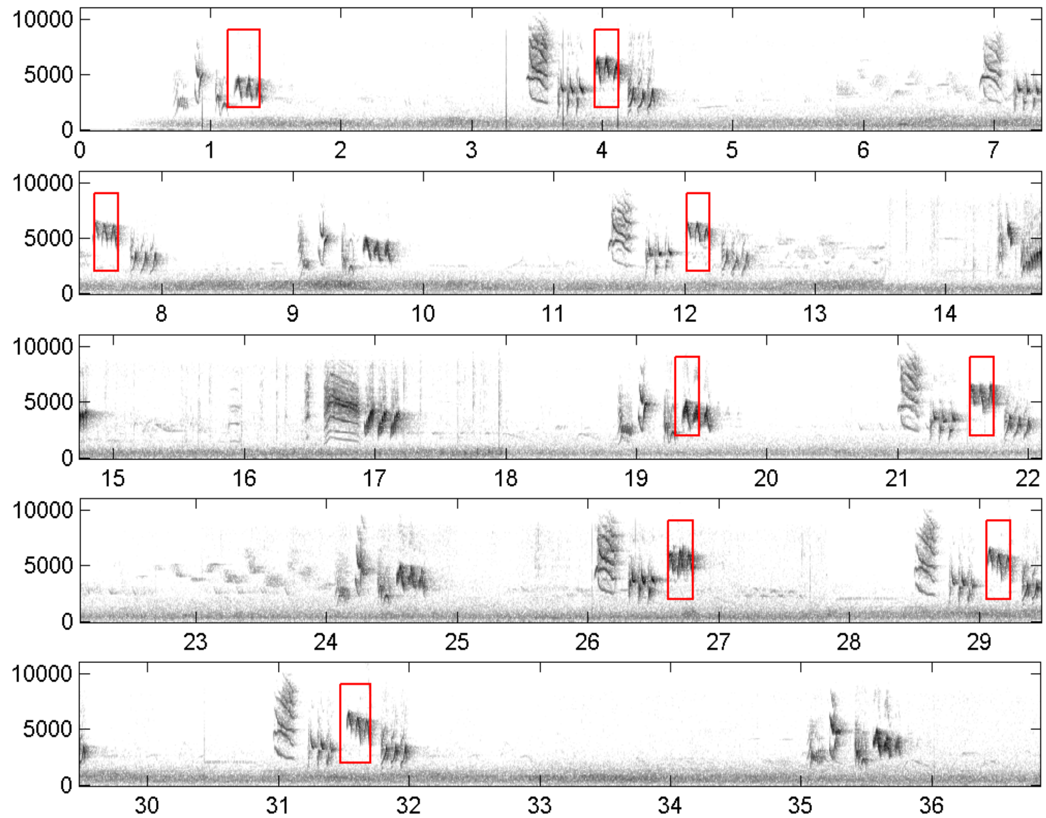
these songs is a rapid series of FM notes that resemble inverted “V” or “U” characters in a spectrogram (Figure 24).

Figure 24. Three black-capped vireo songs,showing characteristic trill sequences of repeated frequency-modulated units.



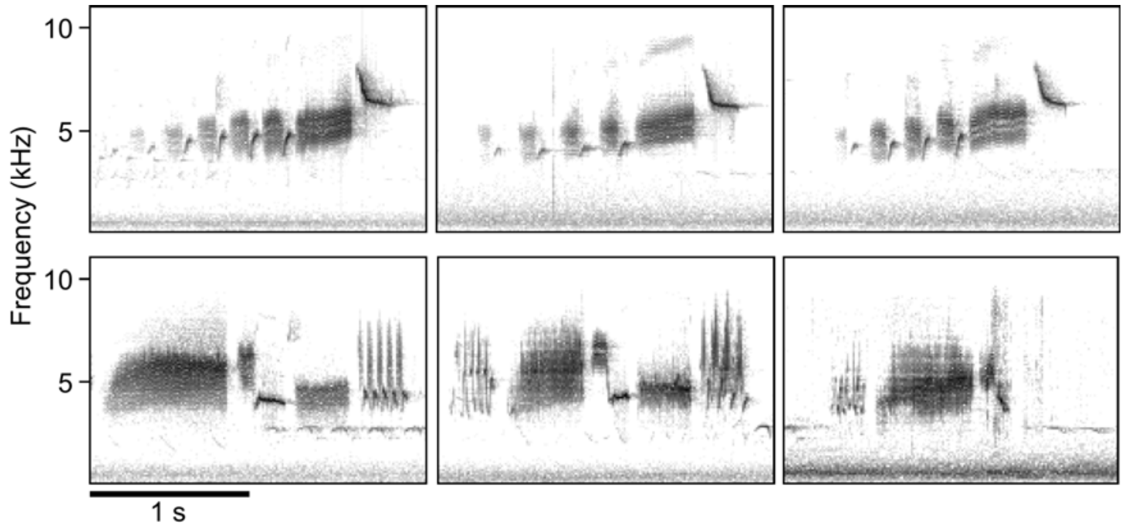
In 2002 we investigated a pitch extraction and tracking algorithm that captured the frequency modulation of the song. Once the pitch contour was extracted, the spectral characteristics of the contour provided a reliable basis for automatic detection. Figure 25 illustrates the results from a prototype detector.

Figure 25. Results of a prototype black-capped vireo song detection algorithm. Horizontal axis: Time (s), vertical axis: frequency (Hz).



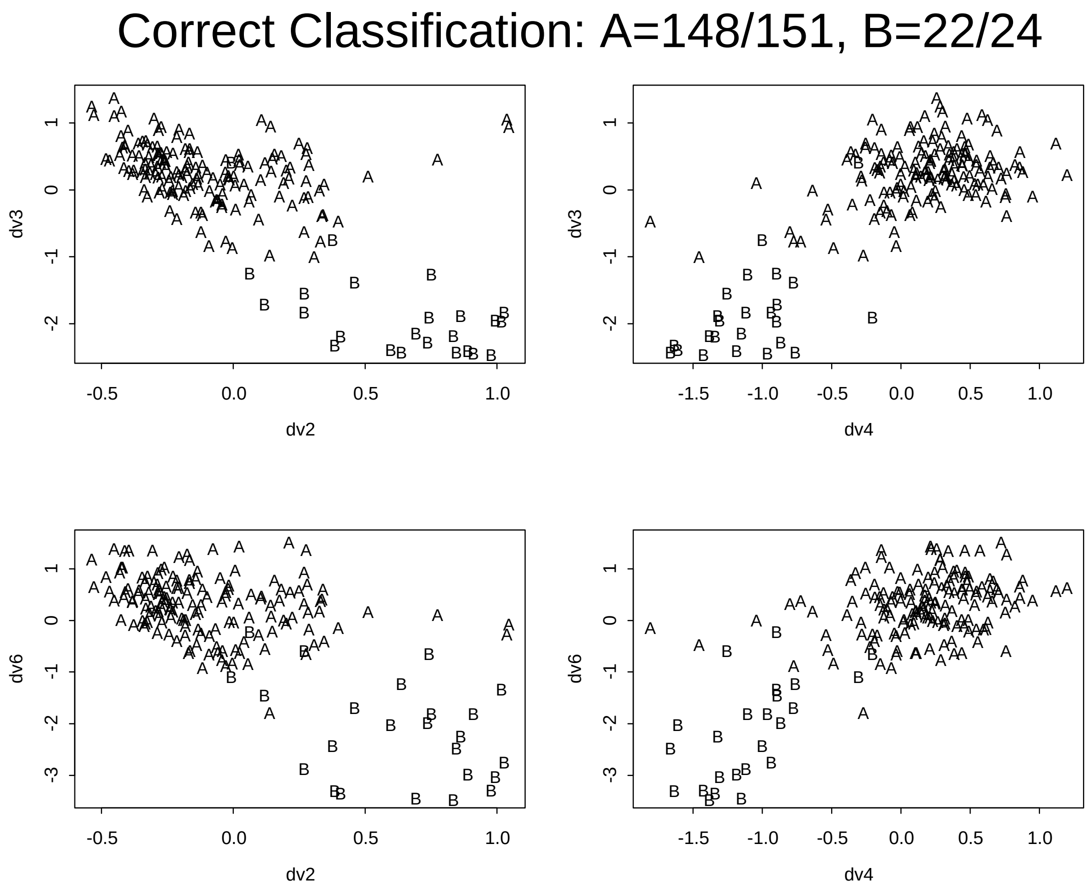
GCWA songs are more stereotyped, and cannot be confused with the songs of any other species present at Fort Hood. In 2002 a preliminary analysis of these songs focused on the potential to automatically distinguish between the Type A and Type B songs (Figure 26, Bolsinger 2000). Type A songs, which are associated with mating displays, are extremely stereotyped and show little variation in structure within or among males. Type B songs, which are associated with territorial interactions among males, are more variable in structure. The capability to automatically distinguish between GCWA song types A and B would enable a recording system to monitor the breeding status of all of the males within range.

Figure 26. Examples of golden-cheeked warbler songs. Upper panels: Type A songs show very little variation in acoustic structure. Lower panels: Type B songs are more variable.



Standardized measurements were extracted from spectrograms of GCWA Type A and B songs (Fristrup and Watkins 1992, 1994), and processed using Linear Discriminant Analysis. The results are displayed in Figure 27. Although there is considerable variation within nominal song types, it is clear that automatic recognition of the A/B song type distinction is practical.

Figure 27. Results of Linear Discriminant Analysis classification of golden-cheeked warbler songs into Type A and Type B (see Figure 26) based on automatically extracted acoustic measurements.



Subsequent development of the pitch contour detector focused on separation of songs in a chorus environment. The goal is to isolate each song, which will then be compared with the signals of interest. If successful, this approach would extend the maximum range of automatic detection, and would enable extraction of more information from dense choruses of birds. Autoregressive pitch estimation algorithms were tested in conjunction with a variety of FM contour tracking methods (Vitterbi, etc.). This vein of development did not come to a conclusion within the scope of this project; but it proved promising enough that work continues.

A substantial acoustical monitoring and analysis effort was devoted to BCVI song detection. The songs of this species are more difficult to identify then GCWA, and there was collateral interest from a separate research project headed by David Delaney of U.S. Corps of Army Engineers, Construction Engineering Research Laboratory, Champaign IL. Table 9 summarizes the BCVI songs collected and analyzed for this collaborative effort. The data from 2002 were not processed due to the small size of the data set and the absence of data across years for comparison.

Candidate BCVI calls were detected using spectrogram correlation (Clark, Marler, and Beeman 1987). A number of spectrogram templates were run on each data set, with templates being added until it became difficult to find BCVI songs that were not detected. This iterative process resulted in larger numbers of templates for larger data sets. Standardized measurements (Cortopassi *in litt.*) were extracted from all sounds that were detected. A subset of the detected sounds were randomly selected and examined to determine whether they were BCVI songs. This subset was used to train a Random Forest classifier (Breiman 2001) using the standardized measurements. The data set was balanced by sound type through replication prior to analysis (Chen, Liaw, and Breiman 2004). The results of the Random Forest analysis are summarized in Table 10. None of the training data that were identified as BCVI songs were incorrectly rejected. An extremely small fraction of the non-BCVI sounds were incorrectly accepted as BCVI. This assessment of error rates used "out of bag" samples: the identified songs used in the test were not used to train that portion of the classifier.

Table 9: Summary of data on automated detection and classification of black-capped vireo song from ARU recordings. Initial detection of candidate BCI songs was by cross-correlation of the signal stream with a variable number of templates manually extracted from the recordings. Subsequent prediction of BCVI specie identity was by a Random Forest classifier operating on tomatically extracted measurements.

Data Set	Channels	Hours	# templates	songs detected	predicted BCVI	BCVI per hour
Dantes Forest 2002	8	6:06:46				
Dantes Forest 2002	12	55:10:47				
Dantes Forest 2002	16	372:27:57				
Vireo Alley 2003	22	237:58:00	12	51,105	8,280	835.07
Vireo Alley 2004	4	405:30:00	14	126,559	5,932	351.09
Vireo Alley 2005	2	5776:35:54	88	1,710,366	271,405	1,127.60
Area 4A 2004	2	317:20:00				
Area 4A 2004	4	44:10:00		168,730	10,126	765.83
Area 4A 2004	6	373:10:00	14			
Blackwell 2004	2	474:00:00	28	23,324	12,716	643.85
Blackwell 2005	2	4193:08:18	28	738,335	56,332	322.42
Jackson Knob 2004	2	278:00:00	9	7,450	698	60.26
Lonestar 2004	2	641:40:00		39,560	2,856	106.82
Lonestar 2004	6	277:35:00	21			
Lonestar 2005	2	5702:11:50	59	1,667,491	116,531	490.47
West Fort Hood 2005	2	3167:59:55	55	466,955	253,742	1,922.29
TOTAL	94	22323:04:27	328	4,999,875	738,618	794.10

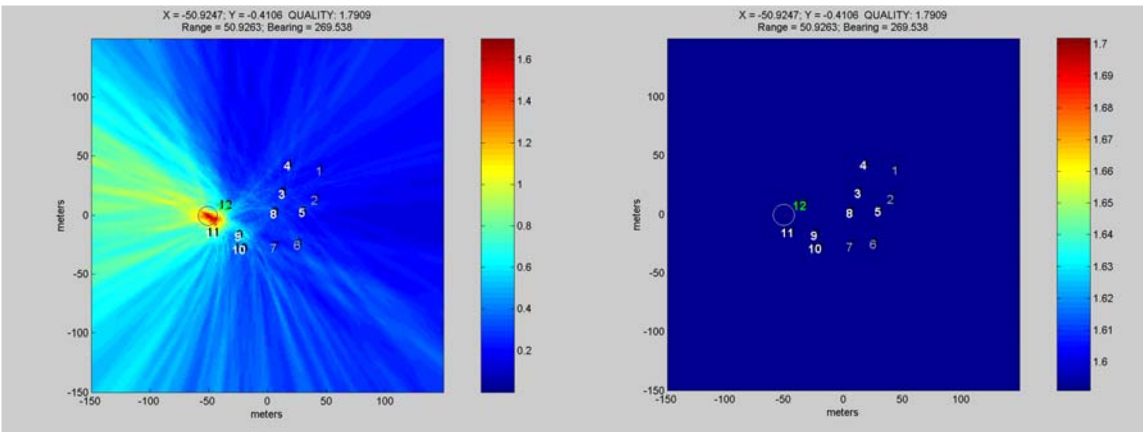
Table 10: Results of human verification of Random Forest classifier performance on BCVI song phrases extracted initially detected by spectrogram cross-correlation.

	False-False	False-True	True-True	Total	percent error
Area4A2004	623	20	80	723	2.77%
Blackwell2004	891	10	1150	2051	0.49%
Blackwell2005	707	14	69	790	1.77%
JacksonKnob2004	115	2	32	149	1.34%
Lonestar2004	1378	15	188	1581	0.95%
Lonestar2005	38	2	2	42	4.76%
VireoAlley2003	1151	45	241	1437	3.13%
VireoAlley2004	1305	28	101	1434	1.95%
VireoAlley2005	26	2	6	34	5.88%
WestFortHood2005	11	2	30	43	4.65%
TOTAL	6245	140	1899	8284	1.69%

Localization

Acoustical localization algorithms were developed and tested during this project, because one realization of the balloon system would have used beamforming to locate the position of each song on the ground. Localization can also be used to identify where each song originates in an array of recorders on the ground. The localization algorithm was implemented as an extension to the XBAT system, so sounds detected automatically with this system can subsequently be fed into the locator. The locator provides empirical error bounds for locations. The noise is measured in the correlation functions, and these measurements are utilized to compute confidence intervals. Figure 28 illustrates the dimensionless beamformed energy surface on the left, and the scaled surface on the right (the range of colors spans six standard deviations, so the 95% interval is represented by the red colors). Given accurate wind and sound speed measurements, localization accuracy of less than a meter is now possible with these bird songs.

Figure 28. Acoustic localization of a single black-capped vireo song, using a 12-channel microphone array. Numbers in white indicate positions of microphones that were used in computing the location estimate; numbers in gray indicate microphones that were not used due to inadequate received signal level. The circle indicates the estimated location. Left: Colors indicate the sum of the cross-correlation functions from all pairs of microphones for each point in space. The highest value is the estimated location of the singing bird. Right: Same data, with colors scaled so that the red area (within the circle) indicates a 95% confidence interval around the estimated location.



Sound source locations are estimated based on the difference in the time of arrival of the signal at spatially separated microphones. In principle, the difference in the time of arrival for each pair of microphones can be measured by finding the time lag at which the maximum occurs in the cross correlation of the signal from the two microphones. However, in a complex sound environment, with many sound sources overlapping in time and frequency, using the maximum value of each correlation as the time delay can produce erroneous results. The high value correlation peaks may refer to more than one source, making it difficult or even impossible to estimate the location of any one source. To overcome this problem, our location method searches for a maximum value across all the correlations simultaneously. Mathematically, we are performing a type of beamforming, searching the x-y space for the place where the correlations line up to give us a maximum sum value. By finding all the correlation values associated with a specific point in space at once, we reduce the error caused by peaks of similar strength that may occur in noisier correlations.

Correlations are calculated from signals recorded on *N* microphones that have been noise equalized and frequency filtered. The initial round of correlations is calculated on a subset of pairs where one channel is the reference signal that was selected manually by an operator inspecting a multi-channel spectrogram display. This channel is cross-correlated with each of the other channels in the array to produce a set of *N*-1 correlations that are most likely to contain high value peaks that relate to the reference signal. The energy normalized cross-correlations that result are used 1) to identify which channels have a clear enough replica of the selected signal to be included in the location process and 2) to identify which portions of the signal on each

channel are likely to contain the replica of the selected sound. Further cross correlations are then produced, using only the portions of the signals that are likely to contain the signal replica. Both the geometry of the array and the information gleaned from the initial subset of correlations determines which sections of each channel are to be used.

In brief, our genetic algorithm treats the initial set of gridded correlation sums as a starting population. The x-y values are paired with a quality value that is the sum of the correlations for the x-y point in space. The starting population of 30,000 gridpoints is trimmed down to the best 1,000 points based on the location quality values. For each trial, two parents are chosen from the population using a random process that is biased in favor of higher quality individuals (*i.e.*, an individual with a higher quality is proportionally more likely to be chosen than one of lower quality). The x and y values of the parents are combined to produced an offspring that falls somewhere between the two parent locations. The offspring value is then randomly jittered to allow for locations not directly on the vector between the parents. The quality of the offspring location is then compared with the qualities of all the individuals currently in the population. If the offspring's quality is higher than any other individual's quality, it is added to the population and the individual with the worst quality is removed. The algorithm runs a maximum of 30,000 loops, but is designed to exit the loop if the population narrows down to a small enough region to constitute a conclusive answer before all the loops have been run. The best 100 members of the final population are stored and the location with the best quality is used as the final location estimate.

Conclusions

This project demonstrated the feasibility of aerial songbird surveys using a small, inexpensive balloon system. With two improvements, the 2004 systems would be a practical tool for surveys of acoustically active animals in a variety of environments. First, the altitude control algorithm needs to be revised to recognize advection events, so it will suspend attempts to adjust buoyancy until the event is over. Second, the helium/water valve needs to be redesigned to increase the aperture of the helium valve. This would permit more rapid deflation of the balloon and correspondingly more predictable landing locations. The value of two-way communications with the balloon was demonstrated in 2004. To improve the value of this communication, it would be helpful to automatically import the navigational data into a commercial mapping product like Delorme Topo 3D, so the people in the recovery vehicle have a live display of the position of the balloon and the vehicle in relation to topographic features, roads, and trails. This balloon platform could be readily adapted for other survey applications: visual or thermal infrared video surveys, bird migration monitoring, possibly even LIDAR surveys.

This report shows that recordings from balloon flights can yield a lot of information about the acoustical behavior of bird species whose sounds are regularly recorded. The typical song intervals for several species were measured using an autocorrelation analysis. The typical range of detection was inferred from plots of song bout durations in relation to maximum allowable

intervals for song linkage. More sophisticated processing steps, like time delay analysis or beamforming of multichannel data, could yield more precise measures of these parameters.

This project also demonstrated the feasibility of automatically collecting and processing enormous volumes of acoustical data to document BCVI singing activity. A byproduct of the balloon design effort was identification of very lightweight, low-cost components for a sensitive, long-term recording system that has very low power consumption. These units were utilized to record tens of thousands of hours of environmental sounds, which were processed to detect and identify nearly three quarters of a million BCVI songs. These methods generalize readily to other vertebrate species. Most other species will pose much less challenging problems for automatic classification than Black-capped Vireos, because this species had a diverse repertoire and it occurs with other species that produce very similar sounds (e. g. White-eyed vireo, Blue-gray Gnatcatcher).

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